NAVY EXPERIMENTAL DIVING UNIT

TECHNICAL MANUAL NO. 01-94

U.S. NAVY UNMANNED TEST METHODS AND PERFORMANCE GOALS FOR UNDERWATER BREATHING APPARATUS

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Reviewed:

D. Junker

D. JUNKER
Unmanned Test Officer/Engineer

B. D. McKinley

B. McKINLEY
LCDR, USN
Senior Projects Officer

M E Knafelc

M. KNAFELC,
CDR, USN
Senior Medical Officer

J. Clarke

J. CLARKE, Ph.D.
Scientific Director

M. LINDSTROM
LCDR, USN
Executive Officer

Approved:

Bert Marsh

BERT MARSH
CDR, USN
Commanding Officer

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Bert Marsh

BERT MARSH
Commanding Officer, NEDU

LIST OF EFFECTIVE PAGES

Insert latest changed pages; dispose of superseded pages in accordance with applicable regulations.

On a changed page, the portion of the text affected by the latest change is indicated by a vertical line in the outer margin of the page. Changes to figures are indicated by miniature pointing hands.

Date of issue for Original Pages is June 1994.

Total number of pages in this document is ___ consisting of the following:

Page Number	*Change Number
Cover	0
Sign Off Page	0
i through x	0
1-1	0
2-1 through 2-3	0
3-1 through 3-20	0
4-1 through 4-50	0
5-1 through 5-10	0
6-1 through 6-7	0
7-1 through 7-8	0
8-1 through 8-n	0
9-1 through 9-2	0

* Zero in this column indicates an original page.

RECORD OF CHANGES

CHANGE NUMBER	DATE	TITLE OR BRIEF DESCRIPTION	ENTERED BY

ORIGINAL

Glossary

ANU	Authorized for Navy Use
ATA	Atmospheres absolute
B/C	Bubble chamber
B/S	Breathing simulator
BPM	Breaths per minute
BTPS	Body Temperature and Pressure, Saturated
°C	Degrees Celsius
CLM	Cowgill, Landstra, Mobley
cm	Centimeters
cmH_2O	Centimeters of water pressure
CO_2	Carbon Dioxide
CSS	Coastal Systems Station, Dahlgren Division
EDF	Experimental Diving Facility (NEDU unmanned test facility)
°F	Degrees Fahrenheit
f	Breathing frequency measured in breaths per minute (BPM)
fsw	Feet of sea water
ft	Feet
HeO_2	Helium-Oxygen gas mixture
HP	High Pressure
ID	Inside diameter
in.	Inches
J/L	Joule per liter (unit breathing effort, equivalent to 1 kPa)
kg•m/L	(old form for breathing effort; aka work of breathing) kilogram meters per liter of respired volume
kPa	kiloPascal (unit of pressure or breathing effort = 1000 Pa)
L	Liters
L/min	Liters per minute
$L \cdot min^{-1}$	Liters per minute (scientific format)
L/sec	Liters per second
LP	Low Pressure
LVDT	Linear voltage displacement transducer
m	Meter
min	Minutes
mg/L	Milligrams liter (water vapor content)
msw	Meters sea water - a unit of pressure

GLOSSARY (cont)

NAVSEA	Naval Sea System Command
NEDU	Navy Experimental Diving Unit
N.I.S.T.	National Institute of Science and Technology (Formerly NBS)
O/B	Over bottom Pressure
O/C	Open-Circuit
OD	Outside Diameter
P	Ambient Pressure
Pa	Pascal = (newton/meter^2)
Po_2	Oxygen partial pressure
psi	Pounds per square inch
psid	Pounds per square inch differential
psig	Pounds per square inch gauge
PTC	Personnel Transfer Capsule
P-V	Pressure - Volume
ΔP	Pressure differential
$\overline{P}_V$	Pressure, volume-averaged (previously, WOB)
R	Gas Exchange Ratio, $R = \dot{V}CO_2/\dot{V}O_2$
RMV	Respiratory Minute Volume. Volume of breathing mixture exhaled by the diver in one minute (measured in Liters per minute)
Resistive Effort	Volume-averaged pressure ($\overline{P}_V$), historically called WOB.
SCUBA	Self-Contained Underwater Breathing Apparatus
% SEV	Percent surface equivalent volume
SLL	Static Lung Load
slpm	Standard Liters Per Minute
Test Mannequin	Semi rigid polymer head sized to cover 93rd percentile
Quasi-Static Pressure/Volume Curve	A pressure volume curve generated by incrementally adding liters of gas to an immersed UBA and measuring the resultant pressure for each liter added.
STPD	Standard Temperature and Pressure (Dry)
Suprasternal Notch	An anatomical reference point for oral/nasal differential pressure
UBA	Underwater Breathing Apparatus
USN	United States Navy

GLOSSARY (cont)

$\dot{V}$	Volumetric flow rate in liters per minute
$\dot{V}CO_2$	Metabolic carbon dioxide production measured in liters per minute
$\dot{V}O_2$	Metabolic oxygen consumption in liters per minute
$\dot{V}max$	Maximum flow rate
V_T	Tidal Volume. Volume of gas that is either inspired or expired by the diver during each breath (measured in liters)
WOB	Resistive Work of Breathing normalized for tidal volume. A measure of pressure averaged over volume, thus removing pressures due to UBA elastance. Consequently, WOB is a volume-averaged pressure, also referred to as Resistive Effort. Currently measured in kPa or Joules/L. Historically, NEDU reported WOB with units of kg•m/l.
ρ	Density
$\propto$	Proportional To
π	3.14159

Conversions

To Convert From	To	Multiply By
kg·m/l	joules per liter (J/L)	9.807
psi	kilopascals (kPa)	6.895
meters sea water	fsw	3.2646
fsw	kilopascals (kPa)	3.063
BAR	psi	14.504
BAR	kPa	100
cmH_2O	kPa	0.0982
J/L	kPa	1.000

Safety Summary

The following are general safety precautions that are not related to any specific procedures; therefore, they do not appear elsewhere in this document. These are recommended precautions that personnel must understand and apply during various phases of testing and evaluation.

STANDARD SAFETY PRECAUTIONS. Operating personnel must observe all applicable safety regulations in compliance with the Navy Occupational Safety and Health (NAVOSH) Program Manual, OPNAVINST 5100.23 Series.

Safety precautions for unmanned testing are normal precautions associated with testing at pressures of 5000 psig or less. To minimize safety risks, operating personnel shall adhere to the test procedures as presented in this report when conducting UBA testing. Failure to perform the procedures as prescribed may result in injury to personnel or damage to equipment.

Table of Contents

List of Illustrations

CHAPTER 1

INTRODUCTION

The Navy Experimental Diving Unit (NEDU) is the United States Navy's facility for the test and evaluation of underwater breathing apparatus (UBA). Every military and commercial UBA considered for use by the U.S. Navy is sent to NEDU for an in-depth evaluation. The evaluation encompasses UBA performance, material suitability, human factors and system reliability. This technical manual is an update of NEDU Report[1] 3-81. It presents the updated unmanned performance goals and test methods currently used by NEDU to evaluate UBA. Chapters 1, 2, and 3 give a general discussion on UBA characteristics and evaluations while Chapter 4 discusses specific instrumentation setup and detailed test methods for specified types of UBA. Chapter 5 describes the analytical software, Chapter 6 details the testing of electronic UBA, and Chapter 7 answers questions about statistical analysis of testing results. Chapter 8 is a mathematical discussion of the work of breathing, resistive effort, and RMS pressure calculations. This section is available from NEDU as a computer file called WOBNEW.mcd; an interactive document for use with MathCad for Windows, version 4.0 or 5.0 running on a DOS style microcomputer.

The instrumentation and test methods described in this manual should allow any hyperbaric test facility to reproduce the tests conducted by NEDU. Any test instrument comparable to that specified in the UBA test setup may be used providing the accuracy and response characteristics of the instrument are equal to or exceed that used by NEDU, and the calibration is traceable to the National Institute of Science and Technology (N.I.S.T) standards.

During the 12 years since the publication of NEDU Report 3-81, microcomputers have firmly established themselves in the testing laboratory. Measurements that were once impractical are now routine. Therefore, much of this document will be devoted to describing the use of microcomputers for testing UBA.

Unfortunately, the mathematical rigor required for the use of microcomputers has emphasized the imprecision of much of the existing UBA testing lexicon. This document attempts to eliminate terminological ambiguities to conform with engineering and scientific convention.

The past decade has seen new research into the effects of UBA elastance on diver performance. Like UBA resistance, UBA elastance can impede a diver's breathing. New design goals for elastance are therefore included in this document.

This document is meant to be dynamic in nature and the methods described are valid as of June 10, 1994. It is not meant to be all inclusive. Experience and individual instruction are still required to conduct accurate tests. As instrumentation technology advances and new test methods are developed, this document will be updated to include changes that will improve the unmanned test simulation.

CHAPTER 2

UBA CATEGORIES

2-1 GENERAL

NEDU has classified UBA into five categories. Each category was selected according to the UBA operational characteristics. Section 2 provides a general description of each category and the operation of each UBA classified within.

- Category 1. Open-circuit Demand UBA
- Category 2. Open-circuit Umbilical Supplied Demand UBA
    - A. Open-circuit Noncompliant Demand UBA
    - B. Open-circuit Compliant Demand UBA
- Category 3. Open-circuit Umbilical Supplied Free Flow UBA
- Category 4. Closed and Semi-closed-circuits, Breath Powered UBA
- Category 5. Semi-closed-circuit, Ejector or Pump-Driven UBA

2-2 CATEGORY 1. DEMAND UBA

All open-circuit SCUBA equipment authorized for Navy use employ a demand system that supplies breathing gas each time the diver inhales. Category 1 is comprised of a first stage regulator, hose, a second stage demand regulator, and a mouthpiece. The purpose of the first stage regulator is to reduce the tank pressure from as much as 310 BAR (4500 psi) to 9.3-11.4 BAR (135-165 psi) over ambient. This reduced pressure is constantly maintained at the second stage. The second stage regulator supplies air through the mouthpiece to the diver on demand and at a pressure equal to the surrounding water pressure. The second stage demand regulator is the central component of the Category 1 UBA; however, the first stage regulator should never be overlooked when evaluating a Category 1 UBA.

Demand regulator assemblies authorized for Navy use consist of two basic types: single-hose and double-hose. Each is a two step system, and differs primarily in the placement of the first and second stage regulators. Category 1 UBAs authorized for Navy use are listed in the Diving Equipment Authorized for Navy Use (ANU) Instruction (NAVSEAINST 10560.2 Series).

2-3 CATEGORY 2. UMBILICAL SUPPLIED DEMAND UBA

Equipment in this category requires either a full face mask or a dry helmet. Each is assumed to have a built-in oral-nasal mask or a mouthpiece.

Category 2 consists of two types of UBA:

A. Open-circuit noncompliant demand UBA. This category covers UBA that provide gas to the diver via a demand regulator attached to an oral-nasal mask in the face mask

or helmet. Examples of UBA in this category include: MK 20.

B. Open-circuit compliant demand UBA. This category contains UBA that supply gas to a diver's helmet via a demand regulator with an oral-nasal mask that is fitted with a neckdam. This category includes MK 21 MOD 0 and MOD 1.

2-4 CATEGORY 3. UMBILICAL SUPPLIED FREE FLOW UBA

UBA in this category also supply gas to the diver via an umbilical, however, the gas constantly flows past the diver's face (no demand required) into the helmet or mask. Excess gas is constantly dumped from the helmet or mask into the water. No oral-nasal mask or mouthpiece is used.

2-5 CATEGORY 4. CLOSED-CIRCUIT, BREATH POWERED

Closed-circuit UBA are divided into two categories: 100% O_2 and constant oxygen partial pressure.

One hundred percent O_2 UBA have no electronics and consist of an oxygen bottle, regulator, breathing bag, and a chemical carbon dioxide scrubber. One hundred percent O_2 is added to the breathing bag prior to diving. As the diver consumes oxygen, the volume in the breathing bag decreases, causing the bag to bottom out on an O_2 add valve attached to the regulator that then flows O_2 into the breathing bag, reinflating the bag. The diver's exhaled carbon dioxide is removed from the UBA by the chemical scrubber. The Draeger Lar V is an example of a closed-circuit O_2 rebreather.

Closed-circuit constant O_2 partial pressure UBA are more complex than the 100% O_2 UBAs, but are also more versatile. This UBA maintains a constant O_2 partial pressure regardless of depth or diver work rate. The UBA consists of a chemical scrubber, electronics, oxygen sensors, breathing bag(s), O_2 bottle, electric O_2 add valve, and a mixed gas bottle. The constant O_2 partial pressure is maintained by the electronics and the O_2 sensors. As O_2 is consumed and the O_2 partial pressure falls below the set point, O_2 is automatically added into the UBA until the set point is reestablished. This cycle is repeated during the entire dive. Carbon dioxide is removed by the chemical scrubber as the gas flows from the diver through the scrubber and into the compliant breathing bag. Examples of this type UBA are the MK 15 and the MK 16.

Semi-closed-circuit UBA function by flowing a constant volume of gas (100% O_2 or O_2 mixed with nitrogen or helium) through a mass flow orifice into the inhalation side of the UBA. This provides a supply of O_2 to the diver, but the O_2 level maintained in the UBA depends upon the diver's work rate. Because gas is constantly added to the UBA, an exhaust regulator periodically dumps gas into the water to keep the UBA from overinflating. Examples of semi-closed-circuit UBAs are the Emerson (MK 6) and the MK 11.

2-6 CATEGORY 5. CLOSED-CIRCUIT, EJECTOR OR PUMP-DRIVEN UBA

An example of the closed-circuit pump driven UBA is the EX 14. The system consists of a helmet, a push-pull pump, umbilicals, and the personnel transfer capsule (PTC). The pump flows a constant preset volume of gas from the PTC to the diver's helmet. The exhaust gas is returned back to the PTC via a second umbilical where the PTC scrubber removes the carbon dioxide.

The semi-closed-circuit MK 12 mixed gas UBA (no longer in use) was an example of an ejector type UBA. It consisted of a helmet, umbilical, back pack with chemical carbon dioxide scrubber, and mass flow orifice. Gas flowed from surface gas banks through an umbilical to a backpack constant mass flow orifice, through the backpack and into the helmet. The gas then flowed from the helmet through the scrubber and back to the helmet. The mass flow ejector assisted in circulating the gas through the UBA. Excess gas was dumped from the helmet into the water through an exhaust valve located on the helmet.

CHAPTER 3

UBA TEST PROCEDURES AND PERFORMANCE GOALS

3-1 GENERAL

3-1.1 Functional Characteristics

A UBA's suitability for diving can be described by up to seven functional characteristics, although not all characteristics apply to all UBA categories. Those characteristics of current interest to NEDU are:

- Peak inhalation and exhalation breathing pressures
- Resistive breathing effort or $\overline{P}_V$
- Elastance
- Hydrostatic imbalance
- Intermediate pressure loss
  - First stage over bottom pressure drop (SCUBA regulators and open-circuit demand helmets)
  - Umbilical pressure drops (surface supplied or PTC supplied umbilical fed UBA)
  - Mask/helmet sideblock and non-return valve pressure loss
- CO_2 control
- Oxygen set point control (closed and semi-closed-circuit UBA)

This section contains a general discussion of each of the seven areas mentioned above. Where appropriate, the rationale for NEDU's use of various test methods or performance goals will be given. The last portion of this section lists the performance goals used by NEDU when evaluating UBAs.

Performance goals are objectives for UBA design engineers and are bench marks for UBA testing. They are NOT acceptance criteria for the simple reason that many types of diving equipment currently in use do not meet the performance goals. Performance goals are not the only requirements that must be met for a UBA to be authorized for Navy use.

3-1.2 Data Acquisition

The digital sampling of pressure and volume data must occur at a rate high enough to faithfully resolve details. At a minimum, the time-varying analog signal should be sampled at a frequency greater than twice the highest frequency present in the signal[2]. Pressure and volume signals should be acquired at more than 100 Hz per channel. NEDU is using a 486 IBM compatible computer with a LABVIEW interface (National Instruments, Austin) to sample 4 channels at 125 Hz per channel.

3-2 SIMULATOR SETTINGS

As a diver's work load varies, his tidal volume (V_T) and breathing frequency (f) alters to meet metabolic demands. These conditions are reproduced in the testing laboratory by using a breathing simulator with various tidal volume and breath per minute settings as shown in Table 3-1.

Table 3-1. Breathing Simulator Standard Settings

f (BPM)	**V_T (Liters)**	**RMV (L/min)**	**Diver Work Rate**
15	1.5	22.5	Light
20	2.0	40.0	Moderately Heavy
25	2.5	62.5	Heavy
30	2.5	75.0	Severe
30	3.0	90.0	Extreme

3-3 VENTILATORY PRESSURES

A differential pressure transducer measures the positive and negative pressures generated during breathing. This respiratory pressure is measured at the Chrome T where inspiratory and expiratory flow is divided during Category 1 tests (Figure 4-3) and in the oral cavity of the test mannequin for Category 2 through 5 UBA. The physical reference point for the ± 7 kPa (± 1 psi) differential pressure transducer is an anatomical landmark called the suprasternal notch which is approximately 17 cm below the mid-oral cavity[3] .

Three types of ventilatory pressures are routinely measured. These are routinely referred to as various mouth pressures since they are measured near the mouth or oro-nasal cavity of an unmanned testing mannequin.

1) Peak inhalation and exhalation pressure - the minimum and maximum pressures found in a P-V loop.

2) Volume-averaged pressure ($\overline{P}_V$), a.k.a. resistive effort, formerly called WOB, which is an average of the pressures contributed by **resistive** components within the UBA.

3) A time-averaged, *effective* pressure called RMS pressure or P_{RMS}. By definition[4,5], RMS pressure measurements respond to all types of pressure within UBA, both **resistive and elastic** (Section 3-5).

Tidal volume is measured by a linear displacement transducer (LVDT) mounted on the breathing machine. An example time tracing of both mouth pressure and tidal volume are shown in Figure 3-1.

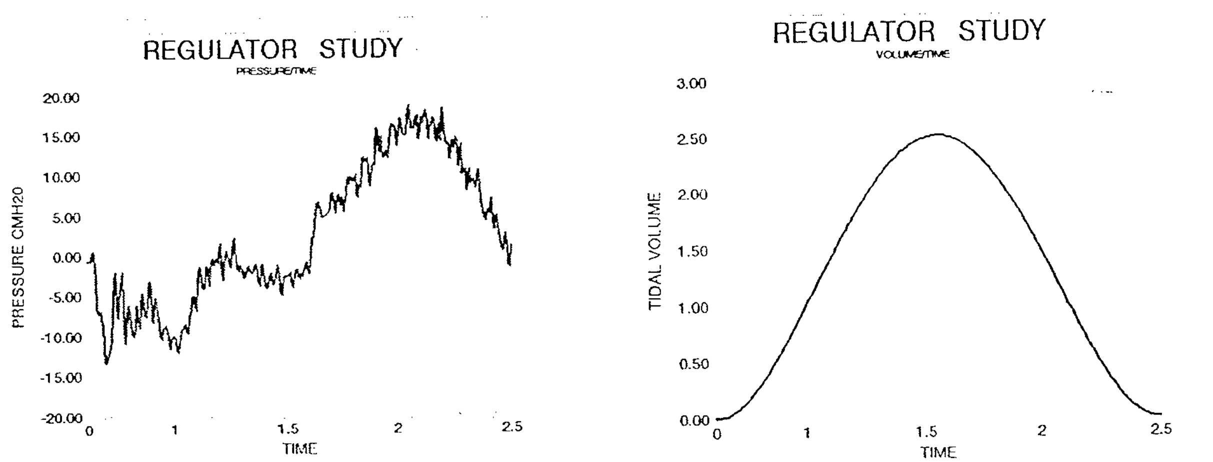


Figure 3-1. Pressure and Volume Tracings (Category 1 or 2)

3-4 WORK OF BREATHING

It is customary to plot pressure against tidal volume, yielding a P-V loop (Figure 3-2). The P-V loop provides useful information because the area inside the loop represents the resistive Work of Breathing. The larger the loop, the greater the work; i.e. the more difficult it is to breathe. Mechanical work (W) is defined as the product of force multiplied by displacement, or for fluid systems, the change in system pressure (ΔP) multiplied by the change in system volume (ΔV). Expressed[6] as an integral, $W = \int PdV$ with units of kg·m or Joules (J).

Within the diving Navy, measurements of work have historically been divided by tidal volume to yield units of kg·m/l, or Joules/liter. This normalized work is frequently associated with the misnomer "Work of Breathing" (WOB). A more proper term would be *volume-averaged pressure* ($\overline{P}_V$), although the descriptive term *resistive effort* also has a proper connotation. These latter two terms will be used interchangeably throughout this document.

Few modern demand regulators are purely non-assisted. Most have venturi, vortex, or pilot assisted boosters to reduce second stage inhalation effort. As a result, while peak inhalation pressures for an assisted and non-assisted regulator may be similar, W and $\overline{P}_V$ for the assisted regulator drops significantly because its peak inhalation pressure occurs for a much shorter period of time. This is illustrated in Figure 3-2 where W, the area enclosed within the loop, is much larger for the non-assisted regulator (bold curve) than for the assisted unit (light curve).

Since successive P-V loops invariably differ due to electrical or mechanical noise, a number of P-V loops are required to ensure statistical validity of the collected data. Typically, 10 breathing loops are acquired, but even 6 iterations provide relatively noise free, average loops. Ensemble-averaging of P-V loops (Figure 3-3 and Section 5.5) reduces random noise without the distorting effects of filters. Figure 3-3 is an extreme example. In the upper portion of the figure the underlying oscillating waveform is obscured by random noise. In the lower plot, ensemble averaging reveals the previously hidden structure (solid black curve). Likewise, the oscillating patterns in Figure 5-1 became clearly discernable only after signal averaging.

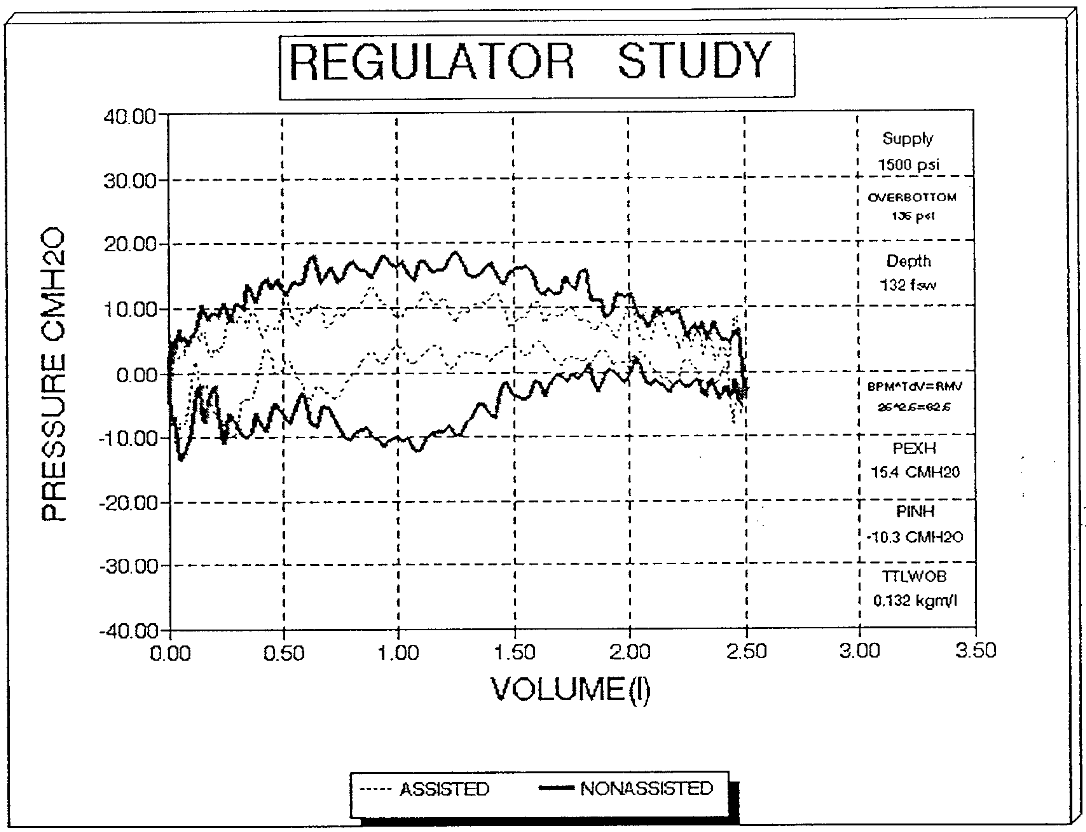


Figure 3-2. P-V Loop (Category 1 or 2 UBA)

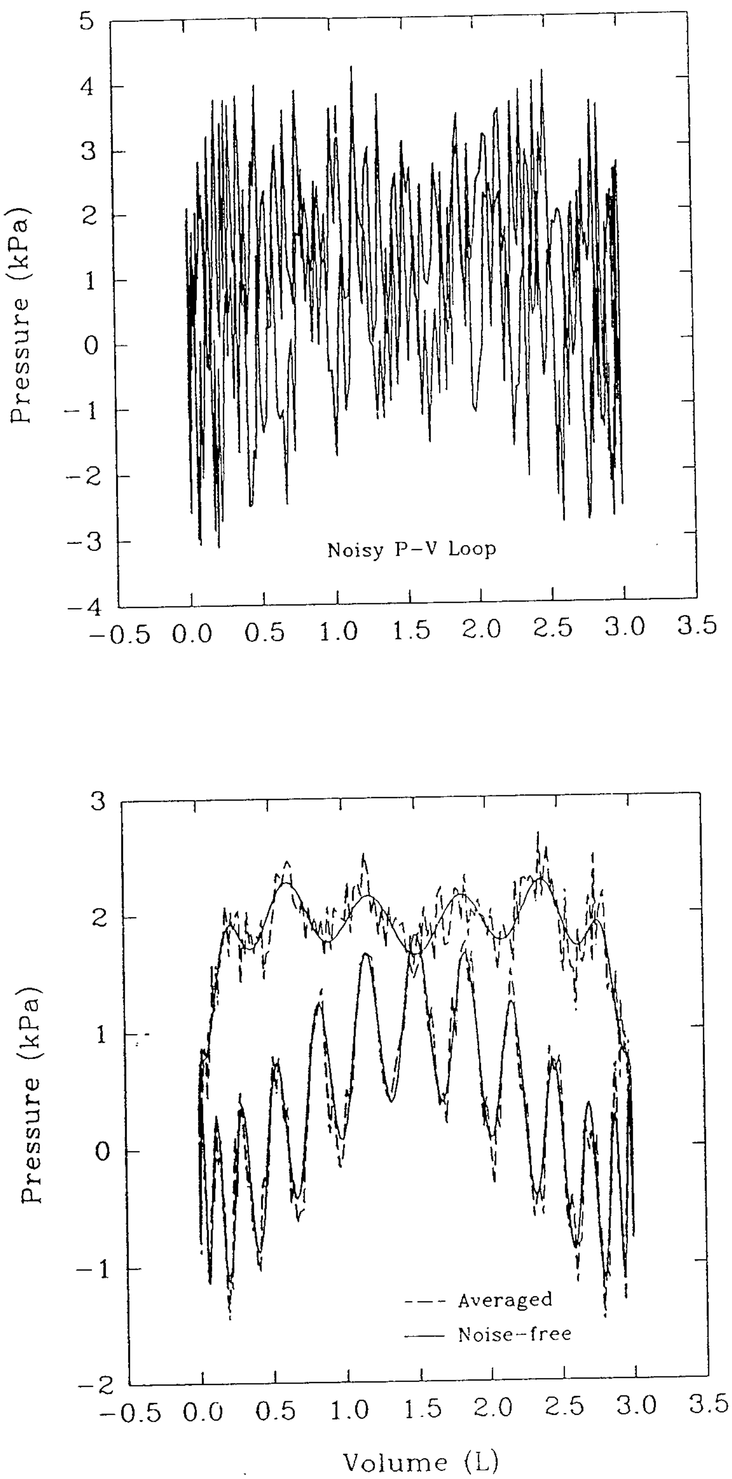


Figure 3-3. Noisy P-V Loop with and without Ensemble Averaging.

3-5 HYDROSTATIC IMBALANCE

3-5.1 What Is It?

The weight of water pressing around a diver's ribcage can make it diffcult for him to breathe unless that inward force is counterbalanced by the outward force of gas fiiling the diver's lungs. If breathing bags are placed high on the chest or back of an upright diver, a pressure imbalance will exist with the inspired gas being at a lower pressure than the mean hydrostatic pressure surrounding the lungs. Relative to the external pressure, the inspired pressure is negative in sign, and therefore a negative pressure balance is said to exist.

To inhale against a negative imbalance a diver has to create highly negative respiratory pressures. Likewise, breathing bags low on a diver means the gas supply is at a higher, more positive, pressure than the hydrostatic pressure surrounding the diver's chest. Therefore, gas flows down a pressure gradient into the diver's lungs. Unfortunately, to exhale, the respiratory muscles must contract forcefully to expel gas back to the breathing bags. Both forceful inhalation or forceful exhalation can result in diver fatigue. Excessively positive pressure can also result in off-gassing of the rig, deplenishing gas supply and endangering covert operations.

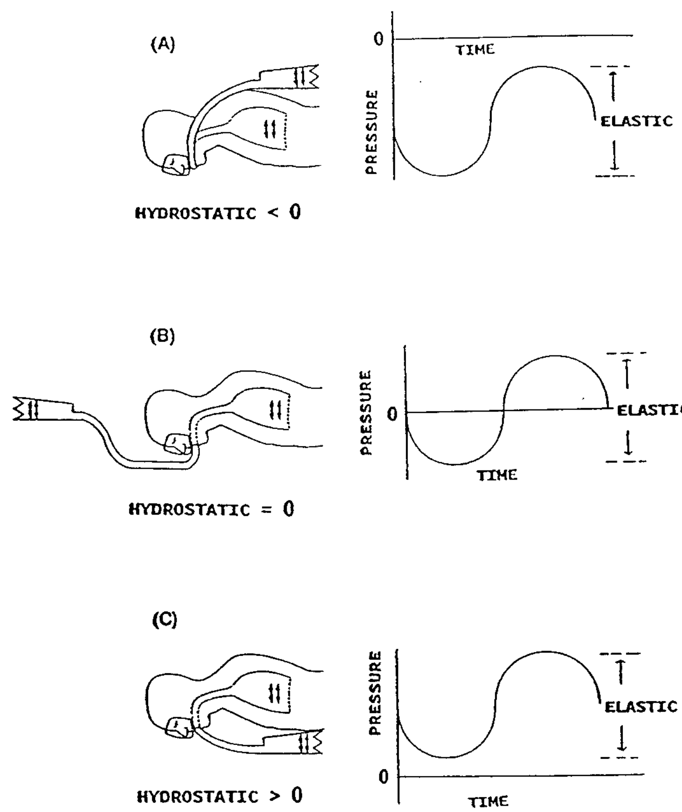


Figure 3-4. Breathing Bag Position and Hydrostatic Imbalance

The effects of hydrostatic imbalances on diver comfort and performance, recently reviewed by Lanphier and Camporesi[7], has been one of the most extensively researched topics in diving physiology during the last decade. The central question has been the following: What respiratory pressures are optimal for counterbalancing the inward force of the water column?

Lung centroid pressure (P_{LC}) appears to be the optimal

pressure for diver comfort during immersion[8]. P_{LC} in upright immersed man is 13.6 cm below the sternal notch, and 7 cm above the plane of the sternal notch in supine (horizontal, face down) man (Figure 3-5). More positive static pressures (up to 20 to 30 cmH_2O) benefit helmeted divers during high ventilatory rates. In tests with MK 15 closed-circuit UBA, the tolerated range of hydrostatic imbalance was relatively large[9]. Therefore, hydrostatic imbalance can range approximately 10 cmH_2O (0.98 kPa) in any direction from the P_{LC} identified in Figure 3-4. For non-helmeted diving, values between P_{LC} and P_{LC}-10 cmH_2O are favored. Lower pressures cause less inflation of the cheeks and oropharynx. For helmeted diving where the upper airways are counterbalanced by helmet pressure, pressures between P_{LC} and P_{LC}+10 cmH_2O are advantageous[10].

3-5.2 Measurement

3-5.2.1 General

In upright man, the suprasternal notch lies approximately 17 cm below the mouth opening (Knafelc, 1988). When a UBA is in the vertical position, the position of the mouthpiece Chrome T is fixed relative to the support for the UBA. The mouthpiece pressure transducer with its integral reference pressure port is secured 17 cm below the Chrome T, with a pressure line attached between the positive side of the transducer and the Chrome T. Therefore, mouthpressure is automatically referenced to a pressure corresponding to the approximate pressure at a diver's suprasternal notch.

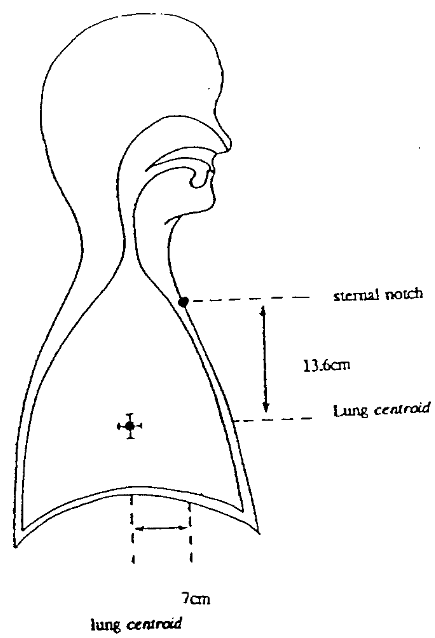


Figure 3-5. Lung Centroid and Suprasternal Notch in an Upright Diver.

Hydrostatic pressure is that pressure which exists in a diver's lungs in the absence of gas flow; hence hydro*static*. However, in elastic UBA, mouth pressure varies with UBA volume even in static, no-flow conditions. Therefore, it is necessary to establish a reference, no-flow condition. We define that condition as end-expiration.

In divers, normal end-inspiration occurs at a volume called FRC, Functional Residual Capacity. In unmanned testing, the reference condition is simply end-expiratory volume. By present convention, "volume" means the volume contained in the breathing machine. Therefore, end-expiration is identified on a P-V loop as a volume of 0 liters.

If the UBA is upright, and the pressure transducer reference port is situated 17 cm below

the submerged mouthpiece, then a reading of 0 kPa with a volume of 0 liters is interpreted as a zero hydrostatic imbalance *referenced to the suprasternal notch.*

Mouth pressure is determined by the location in the water column of the interface between gas and water in the breathing bag. If the reference port on the mouth pressure transducer is located at the same level as the gas-water interface, then a pressure of 0 cmH_2O will be sensed.

3-5.2.2 Specific Procedures

Hydrostatic loading has a great impact on the tolerance of divers to closed-circuit UBA. Therefore, the steps provided below apply to closed-circuit UBA such as the MK 16 and LAR V.

1. All hydrostatic loading tests can be conducted at 1 ATA, with the UBA in both a vertical and prone (face down) position.

2. Mount the UBA in a normal configuration on a mannequin torso reserved for measurements of hydrostatic loading.

3. Mount the Chrome T in a cradle attached to the mannequin frame. This cradle places the Chrome T in an appropriate "mouthpiece" position.

4. Connect the reference port on the mouth pressure transducer to a fitting located at the torso's suprasternal notch. Attach the sensing side to the Chrome T.

5. Apply a three liter tidal volume to the UBA and check the system for leaks.

6. Run the breathing machine with a tidal volume of 3 liters while adding or removing gas from the breathing bag until the P-V loop is relatively linear, with no bends or tails. The loop should be sloping downward to the right. *If the UBA breathing bags will not accomodate a 3 liter tidal volume without tails, then a smaller tidal volume should be used.*

7. Once the UBA breathing bags are in proper trim, and the system is leak-free, no further gas should be added or removed from the system.

8. The hydrostatic load relative to the suprasternal notch is the pressure at the y-intercept (0 volume) of the P-V loop.

3-6 DYNAMIC ELASTANCE

Sloping P-V loops are indicative of UBA elastance (Figure 3-6). Due to the vertical motion of the air-water interface in UBAs with breathing bags or neck dams, a change in UBA volume is associated with a change in system pressure. Elastance presents a respiratory load to

a diver, and is measured by the average slope, $\Delta P/\Delta V$, of the P-V loop[11]. By necessity, peak-to-peak pressure measurements include contributions from both the resistive and elastic components of UBA.

Peak expiratory and inspiratory pressures are identified in Figure 3-6, along with the line of elastance and peak resistive inspiratory pressure (PRIP). The line of elastance connects points of zero flow (maximum and minimum volume) obtained dynamically; i.e. during continuous motion of the breathing machine. The dynamic elastance line approximates the pressure that would be generated during the tidal breath in the absence of resistance. For any given UBA volume, the total mouth pressure is the sum of elastic and resistive pressure.

The dynamic elastance of MK 16 and EX 19 UBA is typically less than 0.7 kPa/L when the UBA breathing bags are properly inflated. Over or under-inflation causes curved P-V loops which markedly elevate both respiratory pressures and the measured dynamic elastance.

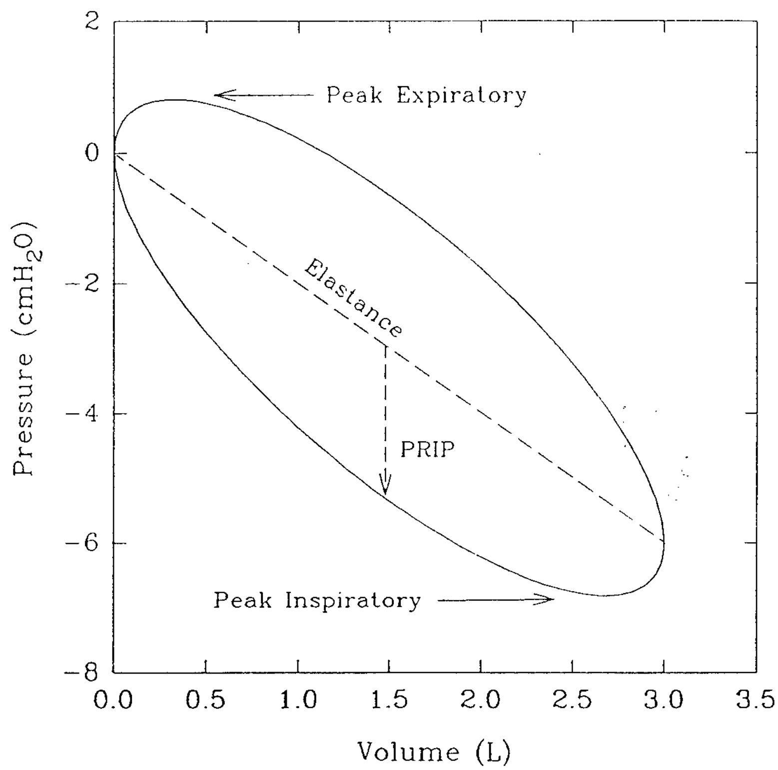


Figure 3-6. P-V Loop in Elastic UBA (Category 4).

3-7 INTERMEDIATE PRESSURE LOSS

3-7.1 First Stage Over Bottom Pressure Drop

The performance of the SCUBA regulator's first stage is critical to the inhalation effort required by the diver. The first stage must supply air at a sufficiently high pressure and volume for the second stage regulator to function properly. As the diver work rate increases, regulator performance degrades mainly due to the failure of the first stage to supply sufficient gas to the second stage.

The spring/valve mechanism of most second stage regulators is designed to function with minimum inhalation effort when supplied with 8.6 to 10.3 BAR (125 to 150 psig) over bottom (O/B) from the first stage. This first stage intermediate pressure is normally set at static or no-flow conditions. Upon inhalation, this pressure drops as the air flows from the first to the

second stage. As a diver descends and work rate increases, the increased flow from the first to the second stage causes the pressure drop from the static setting to increase dramatically. Consequently, the second stage may no longer be receiving air at a rate that meets the diver's inhalation demands, resulting in increased inhalation effort. When the supply pressure to the first stage is below 34.5 BAR (500 psig), UBA efficiency is further reduced. For this reason, Category 1 UBA are always evaluated with a supply pressure between 34.5 and 103.4 BAR (500 and 1,500 psig) to the first stage. To protect the measuring equipment, testing is aborted whenever mouth pressure exceeds $\pm$ 3.93 kPa ($\pm$ 40 cmH_2O).

The maximum intermediate pressure drop from the static setting is measured by attaching a differential pressure transducer to the spare LP port on the first stage. The reference port of the transducer is open to the chamber. By plotting the intermediate pressure drop from the static setting versus depth at each RMV tested, the design limitations of every first stage can be evaluated. Correlating this information with the P-V loop, poor regulator performance can be traced to the first stage, second stage or both. For example, a regulator with a static intermediate pressure of 9.65 BAR (140 psig) O/B can usually operate efficiently with dynamic intermediate pressures as low as 7.93 BAR (115 psig) O/B. Pressure losses greater than this during inhalation generally result in significantly increased inhalation effort. When pressure losses approach 2.76 to 3.45 BAR (40 to 50 psig) less than static, the regulator ceases to function in a manner that can effectively support a diver. Conversely, when a regulator exhibits poor inhalation performance while exhibiting very small intermediate pressure drops, the problem usually exists in the second stage design.

3-7.2 Umbilical Pressure Drop

Umbilical pressure losses have an adverse impact on UBA performance as do the intermediate losses mentioned in the previous paragraph. Gas flow is directly related to supply pressure, umbilical inside diameter (ID) and any added restrictions such as hose splices. Losses incurred within the umbilical can substantially reduce gas supplied to the second stage of a Category 2 UBA. O/B supply pressures in the UBA can be reduced by 10 to 40 percent through umbilical pressure drop. For this reason the correct ID hose should be used with the minimum length required to accomplish the mission. The inability of the pressure to return to the set point between breaths is a strong indication of impending failure.

Pressure drops generally increase linearly with depth in free flow type UBA. However, with demand UBA, the instantaneous flow requirements can be much higher. At high diver RMVs, umbilical pressure drops typically change from linear to an exponential function, sharply increasing breathing effort. While Figure 3-7 is an example of pressure loss in a mask sideblock, the same type of trace will be observed with increases in the umbilical pressure drop.

3-7.3 Mask/Helmet Sideblock and Non-return Valve Pressure Loss

Pressure loss across the sideblock assembly of a UBA can adversely affect breathing resistance. This loss becomes important at or near maximum operating depths where the total

intermediate pressure loss (umbilical ΔP plus sideblock ΔP) is large enough to significantly reduce supply pressure to the UBA's regulator, thereby reducing performance. By correlating this information with P-V loops, changes in breathing work performance can be traced. Figure 3-7 is an example of a dynamic pressure drop graph. As shown, the operation of the sideblock non-return valve was relatively smooth with low cracking pressures.

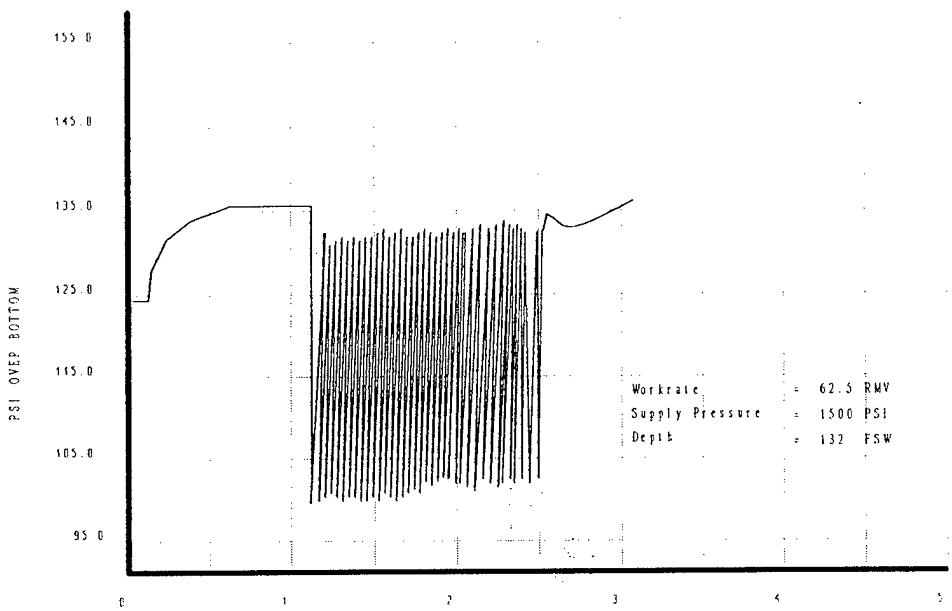


Figure 3-7. Sample Intermediate Pressure (ΔP vs time)

3-8 CO_2 CONTROL

3-8.1 Ventilation Sufficiency

The amount of CO_2 inspired by a diver must be minimized at all times by optimizing fresh gas flow to the diver (ventilation), and by minimizing dead space within the UBA. Dead space is the volume of gas taken in with each breath that contains previously expired CO_2. The larger the dead space, the more difficult it is to eliminate CO_2, and thus the higher the inspired CO_2 level.

Dead space comes from two sources; one within the diver (internal dead space) and one from the diving equipment (external dead space). Internal dead space varies somewhat with individuals and breathing patterns, but on the average is about 150 ml for young, fit men. External dead space can range from a few mLs (SCUBA mouthpiece) to 400-500 mL in some full face masks. In diving helmets, dead space can be even higher. When NEDU is performing unmanned testing, it is of course only concerned with the influence of external dead space.

The NEDU T&E laboratory does not measure dead space *per se* because there are no standards solely addressing this parameter. In fact, a separate standard is unnecessary since it is incorporated into a limit on the CO_2 content of inspired gas (Section 3-10.3). The measurement of ventilation sufficiency is used to confirm the meeting of this requirement. Ventilation sufficiency measurements determine whether or not fresh gas flow is large enough and dead space low enough to allow a safe level of inspired CO_2 under conditions of simulated heavy or severe work (Table 3-1).

The details of the measurement of ventilation sufficiency have been described elsewhere. The following is an overview: Category 3, 4 and 5 UBA are ventilated at an RMV of 75 L/min. A mass flow controller injects 3 L/min (STPD) of 100% CO_2 into the breathing loop. A fast response CO_2 monitor (typically a mass spectrometer) with sensitivity appropriate for the maximum test depth is used to measure breath-by-breath fluctuations in CO_2 measured at the mannequin mouth. If the minimum CO_2 exceeds 2.03 kPa in Category 3 and 5 UBA, then either dead space is too high or fresh gas flow is too low (see Section 3-10.3). For Category 4 UBA, the inspired CO_2 should be no more than 0.27 kPa (2 mmHg) greater than the CO_2 level in the canister effluent.

3-8.2 Canister Durations

It is currently possible to monitor O_2 levels and bottle pressure, but not CO_2 levels within an operationally deployed UBA. Therefore, for safety's sake the duration of the CO2 absorbent canister in a closed-circuit UBA should exceed that of the O_2 bottle supply at all temperatures and depths. Regardless of work rate, the diver could monitor his O_2 consumption with the O_2 bottle gauge and have confidence that the CO_2 scrubber would still be adequate. Unfortunately, this is rarely the case. Alternative means of determining the

useful life of a CO_2 canister are required. Two means now exist: one determines the time required to break through a canister for a particular condition, the other determines the amount of CO_2 the canister can absorb under any condition.

The ratio of carbon dioxide output rate ($\dot{V}CO_2$) to O_2 uptake rate ($\dot{V}O_2$) measured at the lungs is known variously as the respiratory quotient (RQ), respiratory exchange ratio (R), or gas-exchange ratio (R). *The differences between the meaning of these terms are unimportant to this discussion and will not be further addressed except to say we use the term gas-exchange ratio (R) as given in the most authoritative source*[12]. For an exercising individual on a mixed diet of carbohydrates, fat and protein[13,14], R is typically between 0.80 and 0.82. Furthermore, R does not change with hyperbaric conditions[15]. Unless the diver is performing maximal work it is doubtful that the diver's R would exceed this value during extended diving operations. To be conservative, however, R will be assumed as 0.9 for diving operations. That is, CO_2 canisters will be tested with a slightly higher injection rate than is likely to be found in practice.

The performance of CO_2 absorbents may be affected by temperature, depth, gas mixture, and canister design. Hence, at least three different test temperatures and two depths are recommended to obtain a profile of the canister CO_2 absorbency characteristics. Furthermore, to provide statistically useful numbers, at least 5 canisters should be tested for each combination of temperature, depth, and CO_2 injection rate.

NEDU uses a continuous CO_2 injection method for determining canister CO_2 absorbency. Breakthrough is defined as the time until the canister effluent reaches 0.51 kPa (3.8 mmHg or 0.5% SEV). A resting diver is simulated by a continuous CO_2 injection rate of 0.9 $L \cdot min^{-1}$ STPD (Standard Temperature and Pressure, Dry) at an RMV of 22.5 $L \cdot min^{-1}$. This represents R (0.9) times a $\dot{V}O_2$ of 1.0 $L \cdot min^{-1}$. A heavy work rate is simulated by continuously injecting CO_2 at a rate of 2.0 $L \cdot min^{-1}$ STPD at an RMV of 50 $L \cdot min^{-1}$.

3-9 OXYGEN SET POINT CONTROL

Data analysis on oxygen set point control involves simultaneously plotting both percent O_2 in breathing gas and the O_2 addition add valve on/off sequence against time on the same strip chart recorder or equivalent device. Figure 3-8 provides a sample of the dynamic plots generated during testing. These measurements provide all the information required to determine:

1. How closely the UBA is controlling about its set point.

2. How often the O_2 add valve is firing and how long it stays open.

3. The rate change in PO_2 induced by the opening of the O_2 valve; i.e. how quickly the UBA can respond to low PO_2 without overshooting the set point. This equates to the maximum descent rate.

Theory of operation: A given quantity of mixed gas (N_2O_2 or HeO_2) is removed from the UBA breathing loop via a flowmeter calibrated for the correct gas mix to simulate O_2 consumption. The quantity of mixed gas removed is adjusted to contain the desired volumetric flow per unit time. A predetermined amount of inert gas (N_2 or He) is added back into the loop at the same time through another flowmeter to maintain the stability of the inert volumetric balance. Table 3.2 provides a synopsis of mixed gas removal and inert gas addition flow rates for a particular example of a low O_2 consumption (0.64 L/min) and a consumption appropriate for moderate work (1.5 L/min) for depths from 9.14 to 304.8 msw (30 to 1000 fsw). Since R is assumed to be 0.9, the volume of gas returned to the system is 90% of that removed. The overall task of the O_2 consumption simulator is to control by a series of needle valves, and measure by a series of flow meters, the mixed gas removed from and the inert gas added to the breathing loop. The control panel (Figure 4-10) allows the system to shift back and forth from diver rest to diver work conditions.

When other O_2 consumptions are required, new gas removal and addition values can be found in the following manner. To calculate the mix out and inert added at 60 fsw (2.82 ATA) with a PO_2 of 0.7 ATA

$$\% \ O_2 \ mix = \frac{0.70 \ ATA}{2.82 \ ATA} = 0.248 = 24.8\%$$

$$Mixout = \frac{\% \ O_2 \ consumed \ (L/\mathrm{min})}{\% \ O_2 \ mix}$$

For example, if O_2 consumption is 2.0 L/min, then the flowrate **out** of the system would be 2.0 L/min/0.248, or 7.14 L/min.

The return flowrate is simply that withdrawn minus the O_2 consumed; e.g., 7.14 - 2.0 = 5.14 L/min. An additional amount of gas should be returned to the system if additional gas is removed by gas analyzers. For instance, in Table 3-2, 500 mL/min was added to compensate for that removed by analyzers.

The breathing mix is sampled on the *inhalation* side of the UBA breathing loop and analyzed with a rapidly responding O_2 analyzer or mass spectrometer to determine if the UBA is capable of controlling O_2 set point. Section 4-11.5.4 gives specific details about O_2 consumption testing.

Table 3-2. **Summary Table Of Required Flow Rates**

Depth msw (fsw)	Rest Mix Out/Inert Add	Work Mix Out/Inert Add
9.14 (30)	1.75/1.61	4.09/3.09
15.2 (50)	2.30/2.16	5.39/4.39
30.5 (100)	3.68/3.54	8.64/7.64
45.7 (150)	5.07/4.93	11.88/10.88
61.0 (200)	6.46/6.32	15.13/14.13
91.4 (300)	9.23/9.09	21.62/20.62
152.4 (500)	14.77/14.63	34.61/33.61
213.4 (700)	20.31/20.17	47.59/46.59
225.6 (740)	21.41/21.27	50.19/49.19
243.8 (800)	23.08/22.94	54.09/53.09
304.8 (1000)	28.62/28.48	67.08/66.08

NOTE: 0.5 L/min must be added to all inert addition levels to compensate for the O_2 gas analysis sample from the UBA to the gas analyzer. This amount should be verified for the specific O_2 analyzer being used. Table 3-2 has the 0.5 L/min already added.

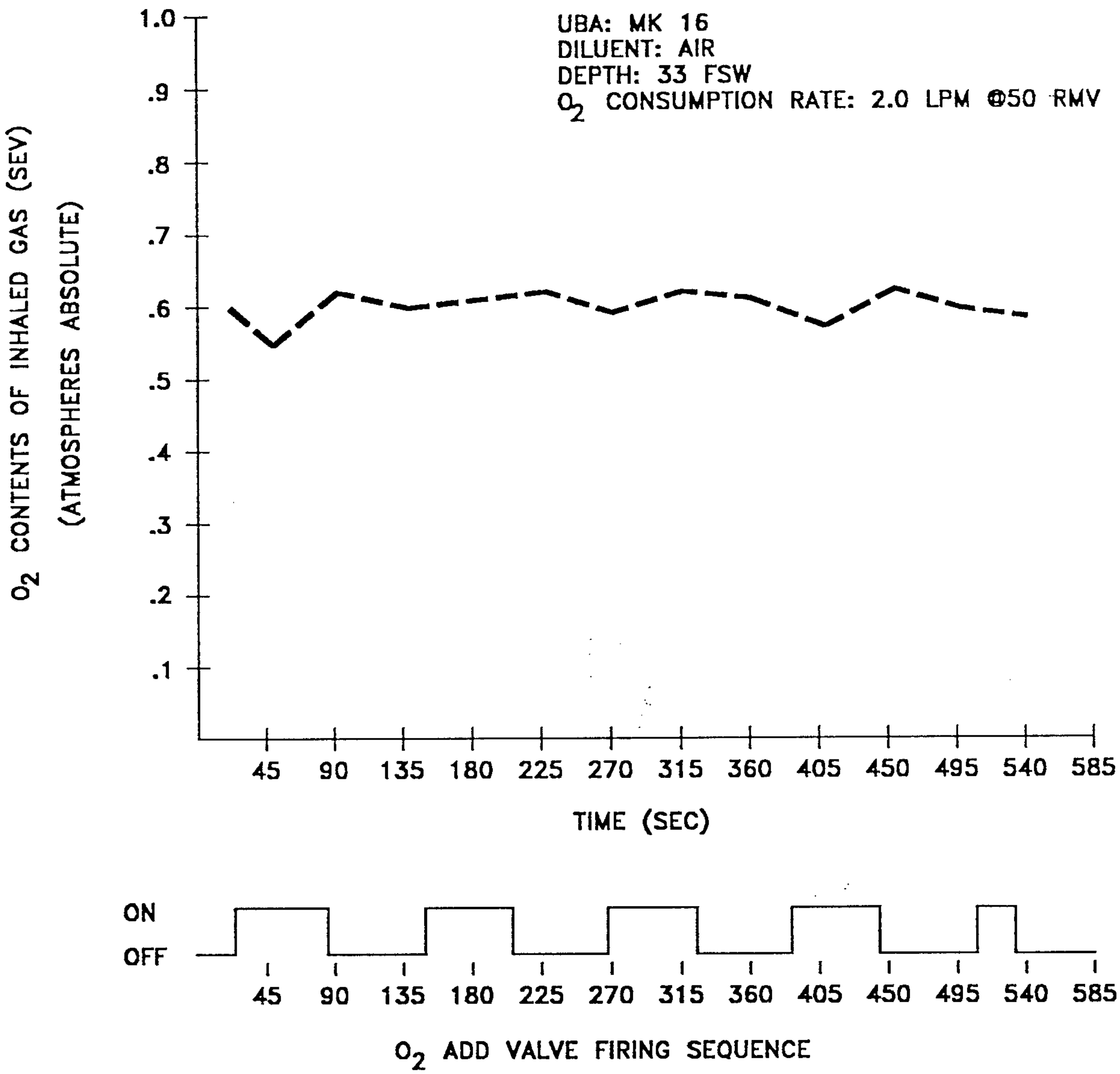


Figure 3-8. O_2 Add vs Time

3-10 PERFORMANCE GOALS

Unmanned test performance goals for resistive effort and maximum ΔP are given in Table 3-3. Maximum ΔP is not by itself adequate for setting goals in Category 1 and 2 UBA. Cracking pressures can be transiently high and do not represent the overall performance of the regulator.

For Categories 3, 4 and 5, the maximum inspiratory and expiratory pressures were chosen by selecting a ΔP (pressure difference from no flow to full inhalation or exhalation) for a particular RMV (say 75 L/min), and then assuming that the ΔP for other RMVs can be found by using a simplified form of Bernoulli's equation. Bernoulli's equation is:

$$\frac{P_1}{\rho g}+\frac{v_1^2}{2g}+Z_1=\frac{P_2}{\rho g}+\frac{v_2^2}{2g}+Z_2$$

where ρ = gas density at depth, g is acceleration of gravity, v is flow velocity, and Z is elevation head. Friction losses are ignored in this form of the equation. By assuming that Z1 = Z2, and rearranging:

$$\Delta P \propto (\dot{V}\mathrm{max})^2 \cdot \rho$$

where $\dot{V}$max = peak flow rate.

The performance goals for ΔP were originally provided in NEDU Report 3-81 in units of cmH_2O. The same goals were retained for this document, after conversion into kPa (10 cmH_2O = 0.982 kPa).

Resistive Effort or $\overline{P}_V$ is measured by dividing the work of breathing (in Joules) by tidal volume (liters). The result is a **volume-averaged pressure** with units of kPa (1 kPa = 1 Joule/liter). By assuming a sine wave input, the expected breathing effort in kPa was found by:

$$\overline{P}_V = \frac{\pi \cdot \Delta P}{2}$$

Historically, resistive effort was expressed in kg·m/L, which required a value of 200 in the above denominator, instead of 2. To convert from kPa to kg·m/L, multiply by 0.102.

3-10.1 Elastance

The goal for elastance is applicable to all UBA. However, elastance is typically a matter of concern only in UBA with breathing bags or neckdams[11]. According to Lundgren[16]

in breathing apparatus designed for prolonged use, elastance should not exceed cmH_2O/liter (0.69 kPa/L). In closed-circuit UBA like the MK 16, elastance is typically below that limit. In operational equipment designed for short term, emergency use, various design constraints result in higher elastances, often ranging between 1 and 2 kPa/L. Those high values are tolerable only because of the short duration of exposure.

3-10.2 Resistive Effort

3-10.2.1 Category 1

3-10.2.1.1 Air Breathing Gas

Mean resistive effort ($\overline{P}_V$) is not to exceed 1.37 J/L (0.14 kg·m/L) at all depths between the surface and 40.4 msw (132 fsw) for an RMV of 62.5 L/min and a supply pressure to the first stage regulator of 103.4 BAR (1500 psig) (see Note 1). For a regulator to be on the ANU list for diving deeper than 40.4 msw (132 fsw) it must pass the above goal at 60.7 msw (198 fsw).

3-10.2.1.2 Statistical Requirements

To test a new regulator for possible inclusion on the ANU list, a minimum of 5 regulators must be tested. The mean resistive effort ($\overline{P}_V$) must not be greater than 1.37 kPa or J/L when tested by simple statistical tests described in Section 7-2.1. If the mean is numerically greater than 1.37 kPa, then the standard deviation (SD) must not be greater than 0.2 kPa.

3-10.2.2 Category 2

3-10.2.2.1 Breathing gas: Air

Resistive effort ($\overline{P}_V$) is not to exceed 1.76 J/L at all depths between the surface and 60.7 msw (198 fsw) for an RMV of 62.5 L/min with regulator supply pressures as per manufacturers' requirements.

3-10.2.2.2 Breathing gas: HeO_2

Resistive effort ($\overline{P}_V$) is not to exceed 1.76 J/L at all depths between the surface and 306.3 msw (1000 fsw) for an RMV of 62.5 L/min with supply pressures as per manufacturers' requirements (see Note 2).

Table 3.3 Performance Goals

					CATEGORY 1 DEPTH 0 to 198 fsw AIR		CATEGORY 2 0 to 198 fsw AIR 0 to 1000 fsw HeO_2		CATEGORIES 3 & 5 0 to 200 fsw AIR 0 to 1500 fsw HeO_2			CATEGORY 4 0 to 150 fsw AIR			CATEGORY 4 0 to 1500 fsw HeO_2		
					RESISTIVE EFFORT		RESISTIVE EFFORT			RESISTIVE EFFORT			RESISTIVE EFFORT			RESISTIVE EFFORT	
$\dot{V}O_2$ (L/min)	RMV (L/min)	V_T (L)	f (BPM)	PEAK FLOW RATE (L/sec)	kg·m/L	kPa (J/L)	kg·m/L	kPa (J/L)	Δ P(3) (kPa)	kg·m/L	kPa (J/L)	Δ P(3) (kPa)	kg·m/L	kPa (J/L)	Δ P(3) (kPa)	kg·m/L	kPa (J/L)
0.90	22.5	1.5	15	1.18	0.14(1)	1.37(1)	0.18(1)	1.76(1)	0.147	0.024	0.231	0.108	0.017	0.170	0.147	0.024	0.231
1.60	40.0	2.0	20	2.09	0.14(1)	1.37(1)	0.18(1)	1.76(1)	0.393	0.063	0.617	0.324	0.052	0.509	0.393	0.063	0.617
2.50	62.5	2.5	25	3.27	0.14(1)	1.37(1)	0.18(1)	1.76(1)	0.982	0.157	1.542	0.746	0.120	1.172	0.982	0.157	1.542
3.00	75.0	2.5	30	3.93	(2)	(2)	(2)	(2)	1.375	0.220	2.159	1.080	0.173	1.696	1.375	0.220	2.159
3.60	90.0	3.0	30	4.71	(2)	(2)	(2)	(2)	1.964(4)	0.315	3.085	1.610(4)	0.258	2.529	1.964(4)	0.315	3.085

Notes: (1) Categories 1 and 2 are not always capable of making the 75 L/min performance requirements at their maximum operating depths. State-of-the-art in open-circuit demand UBA is such that 62.5 L/min is the limit for reasonable breathing work values.

(2) No work of breathing goal is established for Category 1 and 2 RMVs greater than 62.5 L/Min, however UBAs may be evaluated at 75 and 90 L/Min if capable of performing at these higher work rates.

(3) ΔP max is measured from neutral (no flow) to full inhalation or exhalation.

(4) An RMV of 90 L/min is of interest to verify system performance but 75 L/min is the actual performance goal.

3-10.2.3 Category 3

3-10.2.3.1 Breathing gas: Air

Resistive effort ($\overline{P}_V$) is not to exceed 2.16 kPa and peak inhalation and exhalation pressures are not to exceed 1.38 kPa (14 cmH_2O) positive or negativc at all depths from the surface to 61.26 msw (200 fsw) at an RMV of 75 L/min (see Note 3).

3-10.2.4 Category 4:

3-10.2.4.1 Breathing gas: Air

Resistive effort ($\overline{P}_V$) is not to exceed 1.70 kPa and peak inhalation and exhalation pressures are not to exceed 1.08 kPa (11 cmH_2O) positive or negative at all depths from the surface to 45.95 msw (150 fsw) at work rates up to and including an RMV of 75 L/min (see Note 3).

3-10.2.4.2 Breathing gas: HeO_2

(a) Resistive effort ($\overline{P}_V$) is not to exceed 2.16 kPa and peak inhalation and exhalation pressures are not to exceed 1.38 kPa (14 cmH_2O) positive or negative at all depths from the surface to 459.5 msw (1500 fsw) at RMVs up to and including 75 L/min (see Note 3).

(b) In closed or semi-closed-circuit UBA, static lung loading (SLL) is defined as the pressure in the system with no gas flow in the breathing loop. System pressure shall be referenced to the suprasternal notch; i.e., measured as a differential pressure between the mouth and the suprasternal notch of the testing manikin.

The optimal value for SLL should be 0 cmH_2O in both the upright and prone position, and should not exceed 9.82 kPa (+10 cmH_2O). SLL shall be no less than -.982 kPa (-10 cmH_2O) in the prone position, and no less than -.196 kPa (-2 cmH_2O) in the upright position.

3-10.2.5 Category 5

3-10.2.5.1 Breathing gas: Air

Resistive effort ($\overline{P}_V$) is not to exceed 2.16 kPa and peak inhalation and exhalation pressures are not to exceed 1.38 kPa (14 cmH_2O) positive or negative at all depths from the surface to 61.3 msw (200 fsw) at RMVs up to and including 75 L/min (see Note 3).

3-10.2.5.2 Breathing gas: HeO_2

$\overline{P}_V$ is not to exceed 2.16 kPa and peak inhalation and exhalation pressures are not to

exceed 1.38 kPa (14 cmH_2O) positive or negative at all depths from the surface to 459.5 msw (1500 fsw) at RMVs up to and including 75 L/min. (see Note 3).

3-10.3 CO_2 Control

Inspired CO_2 levels are minimized by reducing dead space, increasing ventilation, and maintaining CO_2 scrubber efficiency. The applicability of the above strategies depends upon the type of UBA being tested. For that reason, CO_2 control limits differ, depending on the Category of UBA.

Ventilation Sufficiency:

Category 1: Not applicable.

Category 2: Inspired CO_2 levels at the mouth shall be no greater than .267 kPa (2 mmHg) more than the supply gas CO_2 at an RMV of 62.5 L/min at all depths from the surface to 40.4 msw (132 fsw) on air and from the surface to 306.3 msw (1000 fsw) on HeO_2.

Category 3: Inspired CO_2 should be less than or equal to 2.03 kPa (15.2 mmHg, 2% surface equivalent) at an RMV of 75 L/min with a CO_2 injection rate of 3.0 L/min.

Category 4: Inspired CO_2 levels at the mouth shall be no greater than 0.267 kPa (2 mmHg) more than canister effluent at an RMV of 75 L/min with a CO_2 injection rate of 3.0 L/min.

Category 5: Maximum allowable CO_2 level in the mask or helmet is to be less than 2.0% SEV 2.03 kPa (15.2 mmHg) at an RMV of 75 L/min with a CO_2 injection rate of 3.0 L/min.

Scrubbing Efficiency:

Unmanned canister capacity is the mean of at least five individual data points obtained under identical conditions. The individual capacities are those required for the canister effluent to consistently exceed 0.5% SEV (0.507 kPa, 3.8 mmHg) during the canister performance study. Unmanned canister capacity represents the average time a canister will keep effluent CO_2 below 0.5% SEV (0.507 kPa, 3.8 mmHg).

3-10.4 Summary

The following sub-sections expand on the information provided in the notes of Table 3-3. A summary of all performance goals in each category of UBA is given in Table 3-3.

3-10.4.1 Note 1:

This goal is based upon a NEDU Report 2-80 that evaluated commercially available SCUBA regulators. Only seven regulators met the above goal with another 23 being close. The value of 1.37 kPa at an RMV of 62.5 L/min and 40.4 msw (132 fsw) was obtained by examining the data to find the point at which state-of-the-art equipment significantly outperformed the rest of the group. The 75 L/min RMV goals of Categories 3 through 5 are not routinely attainable in Categories 1 and 2 UBAs, consequently, Categories 1 and 2 have performance goals at shallower depths and lower RMVs than do Categories 3 through 5. However, if a UBA is capable of performing at 75 and/or 90 L/min, testing is encouraged.

3-10.4.2 Note 2:

The value of 1.76 kPa at an RMV of 62.5 L/min represents the maximum performance that can be expected from state-of-the-art equipment in Category 2, based upon unmanned tests performed at NEDU. UBA should be tested at RMVs of 75 or 90 L/min if at all possible.

The performance goal for Category 2 differs from Category 1 because conventional SCUBA regulators receive gas from the first stage between 8.62 - 10.34 BAR (125 to 150 psig) over bottom. Most demand regulators in Category 2 have over bottom pressure settings between 9.31 to 12.41 BAR (135 to 180 psig) O/B at the diving console. The UBA then receives gas to the second stage at only 5.17 to 7.93 BAR (75 to 115 psig) over bottom due to pressure losses in the umbilical and mask sideblock. Consequently, it is reasonable to expect a slightly reduced level of performance in Category 2 compared to Category 1.

3-10.4.3 Note 3:

An RMV of 75 L/min has been proven in both manned and unmanned testing as a reasonable performance goal in Categories 3 through 5. It will ensure that the UBA is not the limiting factor in diver performance.

CHAPTER 4

CALIBRATION AND TEST METHODS

4-1 GENERAL

This chapter covers calibration procedures for instrumentation, required test equipment, setup of unmanned tests, test procedures for the five categories of UBA, and general guidelines for data gathering.

Before testing can begin, the results of all pertinent baseline calibrations must be written into the test log book, reviewed and approved by the test director. During the course of testing, if any part of the sensing system is subjected to over-range or requires replacement, recalibration will be necessary.

4-2 DATA ACQUISITION AND ANALYSIS

NEDU's data acquisition system is capable of acquiring and processing greater than 125 samples/second/channel. The data analysis program was custom written in the C programming language, and incorporates National Instruments' Labwindows graphic routines. Outputs are provided to a monitor and a Hewlett Packard Laserjet IV printer. The system takes the measured readouts from the pressure and volume instruments, and records P-V data for 10 respiratory cycles. A breathing loop that has been mathematically averaged (ensemble averaged) is then displayed along with its peak pressures and breathing effort. The "Y" axis (ordinate) is the "mouth" pressure in kPa, and the abscissa or "X axis" is the volume of gas in liters "exhaled" by the breathing machine.

The area within the P-V loop (representing work) is calculated using the trapezoidal method of integration. The value for work is then divided by tidal volume yielding a volume-averaged pressure with units of kPa or J/L. Figure 3-2 is an example of a representative P-V loop and the information generated by this analysis program. Pressure and volume data as a function of time is written to a spreadsheet file. Following each days run, all test data is archived.

4-3 CALIBRATION "UBA"

4-3.1 NEDU CLM Calibration Orifice

The NEDU calibration orifice, Figure 4-1, designed and developed by Cowgill, Landstra, and Mobley (CLM), is used to conduct the daily cal check of the breathing simulator. The orifice is a highly polished cylinder, and because the physical dimensions are fixed, resistive WOB values will be constant for each RMV. The purpose of the orifice is to provide a relatively fixed breathing resistance. The orifice is placed where the mouthpiece of the UBA will be placed during actual UBA tests. The breathing machine is then operated at 1 ATA, and a P-V

loop recorded for each RMV. The calculated effort is then compared against tolerance limits established for each RMV (Table 4.1). The testing computer graphically displays the measured effort along with the tolerance limits (tolerance limits were established at 2 standard deviations above and below the mean of approved orifice checks. Example orifice calibration loops are found in Figure 4-2. If the orifice calibration check falls outside tolerance limits, then a problem exists, such as excess volume in the circuit, high flow resistance, improper transducer calibration, or water trapped in various lines and hoses.

Table 4-1. CLM Orifice Calibration Values (Daily Calibration)

RMV (L/min)	minimum $\overline{P}_V$ (kPa or J/L)	maximum $\overline{P}_V$	mean $\overline{P}_V$
22.5	0.17	0.31	0.24
40.0	0.70	0.82	0.76
62.5	1.58	1.84	1.71
75.0	2.17	2.45	2.31
90.0	3.10	3.43	3.26

4-3.2 Calibration Elastance

The NEDU Standard Elastance is obtained by using a straight-sided acrylic cylinder 5 in (12.7 cm) in diameter immersed vertically in water. Gas from the breathing machine enters the cylinder through the top. Its volume is adequate to contain a 3-L tidal volume. The elastance of this cylinder[11] is by calculation 7.885 cmH_2O/L (0.774 kPa/L). This value lies just above the elastance performance goal[16] of 7 cmH_2O/L.

4-4 COLLINS CHROME T

The Warren E. Collins Chrome T (Figure 4-3) serves as the mouth of a diver. The Chrome T is a T-shaped pipe with check valves that allow flow to and from the breathing simulator via two separate hoses. Mouth pressures for category 1 UBA, and inspired/expired temperatures are measured at the Chrome T unless otherwise specified in the approved test plan.

4-5 BREATHING SIMULATOR

The respiratory simulator is a noncompliant device that is calibrated to move a prescribed volume at the Chrome T of up to 3.0 liters at a controlled rate of up to 30 BPM. RMV is controllable to within $\pm$ 0.01 L/stroke. The inhalation and exhalation paths are separated by routing valves for better control of heat, relative humidity, and carbon dioxide. NEDU uses two

103.4 BAR (1500 psig) breathing simulators, one built by Reimers Engineering (Model 1500, Alexandria, VA) and one built by Battelle (Columbus OH). The Battelle machine is computer controlled. These simulators are the "lungs" of the unmanned testing laboratory and must be precisely setup and calibrated before and after each dive.

The stroke volume of the breathing machine is checked during two periodic tests. A quarterly calibration is performed upon installation of the breathing simulator, following repair or overhaul, and every three months thereafter. This test is accomplished by measuring with a Collins chain compensated gasometer the total volume output from the outlet of the Chrome T at 1 ATA and four combinations of frequency and stroke volume (Table 4-2). The total volume is then divided by the number of strokes. The per stroke error should be less than 0.01 L. The second check is a daily calibration check run before and after each dive using the CLM calibrated orifice.

4-5.1 Quarterly Calibration

This test ensures that the total RMV flows from the outlet of the Chrome T into the UBA, thereby identifying any system leaks or breathing piston blow-by. The test is conducted at four different tidal volumes and the four different breathing rates indicated in Table 4.2.

Table 4-2 Quarterly Calibration Settings

Volume (Liters)	Strokes (Hz)	Total (Liters)
1.5	60	90
2.0	45	90
2.5	36	90
3.0	30	90

4-5.2 Daily Calibration

The daily calibration occurs in three stages; a pressure calibration, a volume calibration, and a system calibration check.

1. First, a two point calibration is carried out on the positive side of the Keller PSI mouthpresure transducer ($\pm$ 1 psi) attached to the Chrome T. Pressure levels of 0 kPa and 4 kPa are produced and verified by a Heise 0-2 psig digital pressure gauge. *(The Heise gauge is in turn calibrated by the Navy's METCAL facility at 6 month intervals.)* The resulting voltages are sensed by the DOS based data acquisition computer and used by the calibration program described in Section 5-1.2 of this manual.

2. A 5 point calibration is then performed on the breathing machine LVDT volume transducer. Calculated LVDT transducer coefficients are computed and stored in a file along with the pressure transducer coefficients.

3. The integrity of the overall system is checked by measuring the breathing effort of the NEDU CLM calibrated orifice, Figure 4-1. The orifice has a fixed internal diameter that offers a constant, repetitive resistance to flow. The resistive WOB baseline is performed at 1 ATA by inserting the orifice into the Collins Chrome T (Figure 4-3) and operating the breathing machine at RMVs of 22.5, 40, 62.5, 75, and 90 L/min. The resistive WOB for each setting is shown in Table 4.1 and the corresponding P-V loops are shown in Figure 4-2.

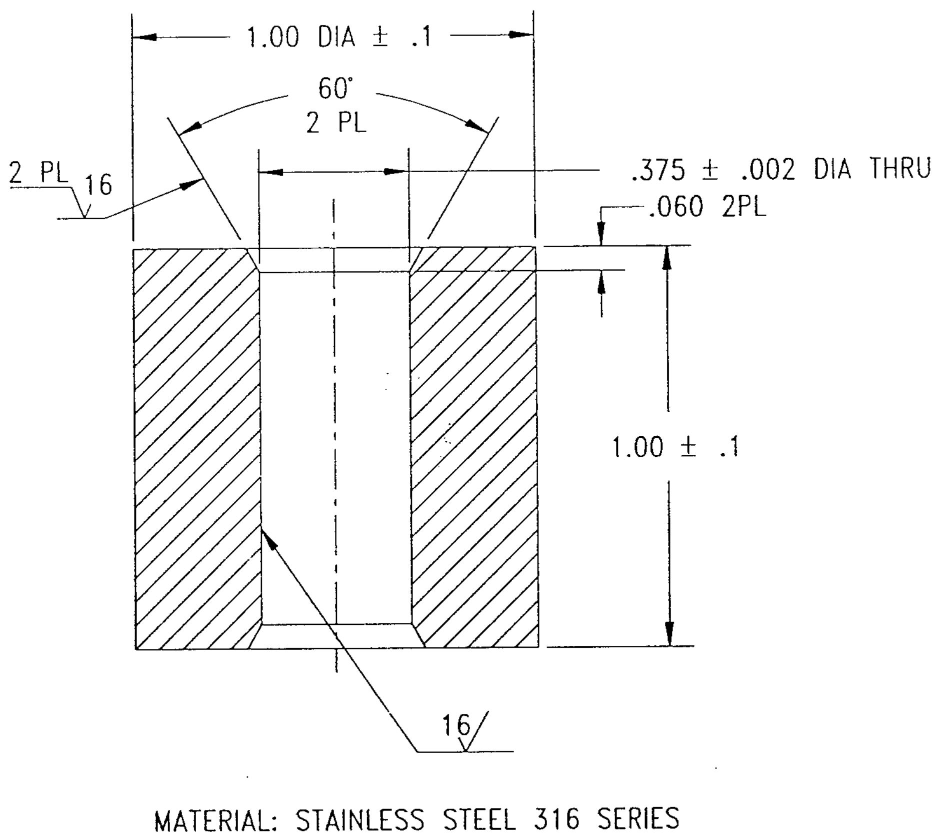


Figure 4-1. NEDU CLM Calibration Orifice

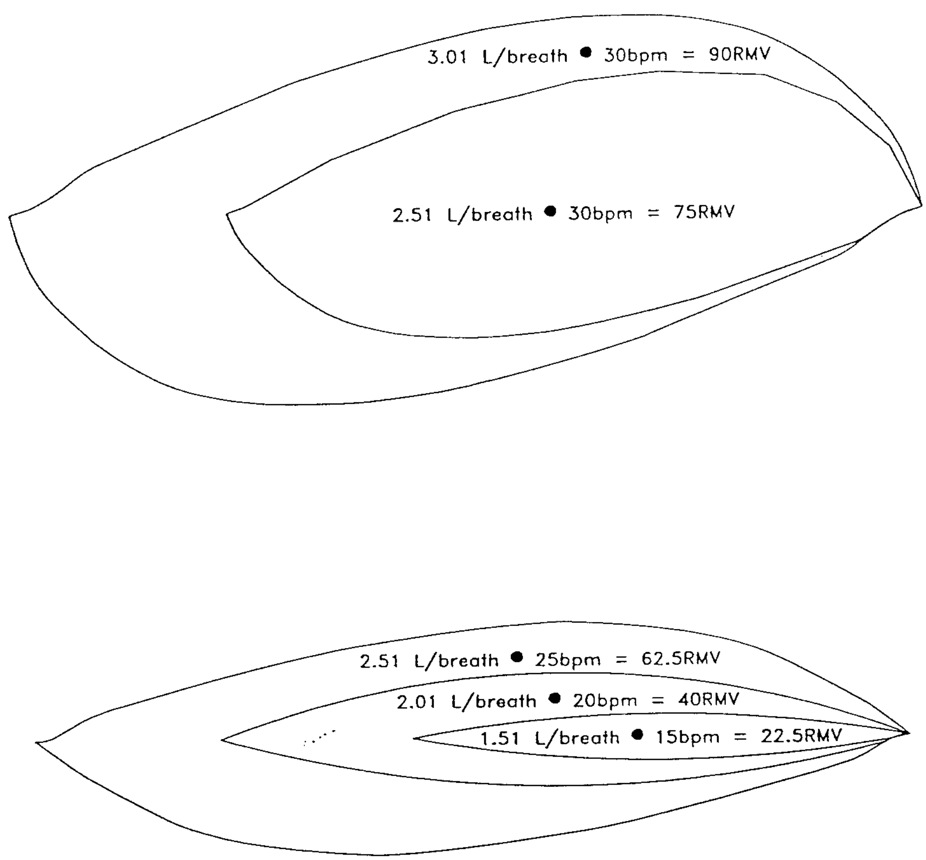


Figure 4-2. P-V Loops (NEDU CLM Calibration Orifice)

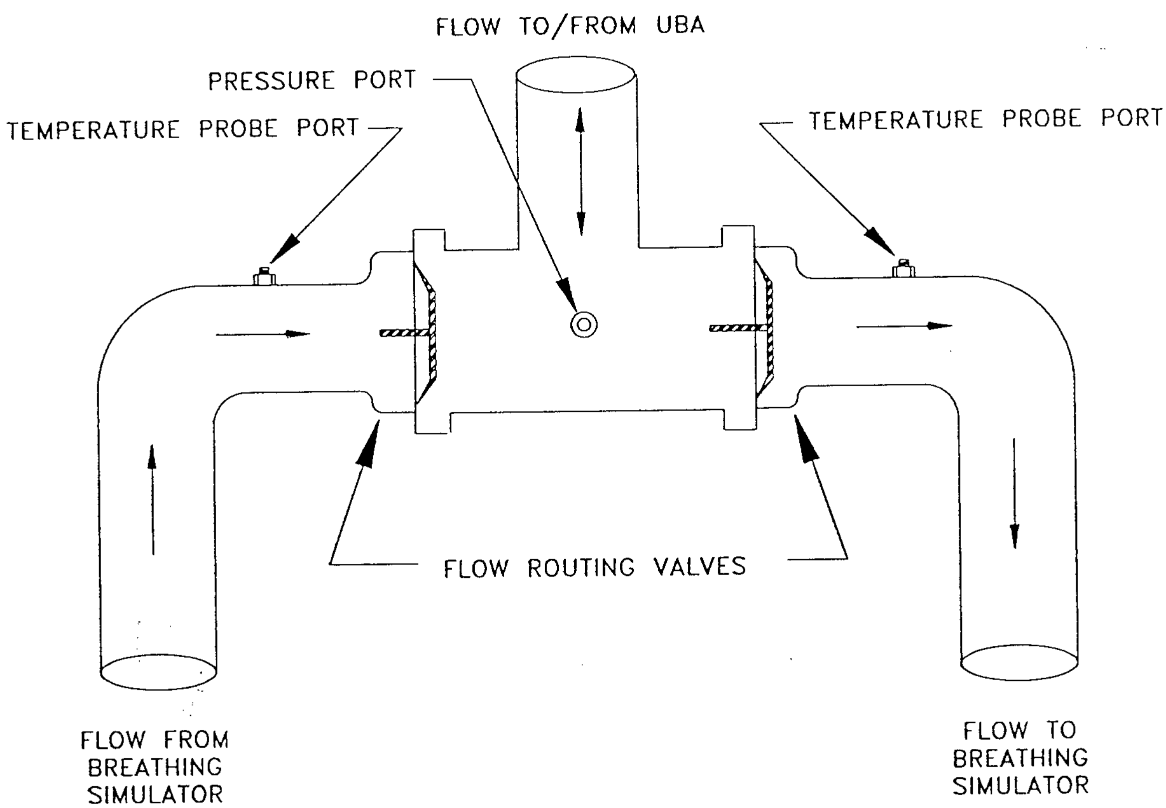


Figure 4-3. Collins Chrome T

During daily calibration, the linear voltage displacement transducer (LVDT) should be tracked by the computer and on the X/Y plotter, if used. The voltage reading at the end point of inhalation and exhalation will change as the RMV changes. Therefore, this voltage reading should be measured for each RMV setting to avoid incorrect tidal volume readings. If a rapid scanning computer is not available, a digital oscilloscope should be used to track the P-V loops. This will allow validation of the X/Y plotter used to record P-V loops. The test setup should be adjusted until repeatable results are within the established parameters.

P-V loops generated from the calibration orifice are generally asymetrical (Figure 4-4), presumably due to the compliance of the long breathing hose between the breathing machine and the Chrome T inside the chamber. The skewing is typically less pronounced at elevated ambient pressure due to a stiffening of the hoses and the gas within them. The line with dots in Figure 4-4 represents a skewed loop, and the solid line represents a corrected loop. Figure 4-5 documents pipe and hose lengths for one NEDU test chamber setup. Methods for correcting for testing system compliance have been described[11].

4-5.3 Elastance Calibration

If a UBA with an appreciable elastance is to be tested (closed-circuit UBA or helmet with neck dam), the test should be preceded by use of the NEDU Standard Elastance. If all systems are working correctly, the computer should return an elastance measurement of 0.77 ± 0.1 kPa/L when run **without** the CLM orifice. Actual UBA tests should not proceed until this elastance value is repeatibly reproduced.

4-5.4 Temperature Calibration and Corrections

Temperature probes should be calibrated over the range of 25°F to 125°F using as a standard the Hewlett Packard Model 2804A Quartz Thermometer. Slope and offset for each sensor should be calculated and recorded in the test logs.

When calibrating the breathing machine, it is essential that both the breathing and the calibration device, for example a Tissot spirometer, be at the same temperature and humidity conditions, or that an appropriate correction be applied. If the breathing machine is warmer than the spirometer, then the volume measured by the spirometer will be less than that actually delivered at the outlet of the breathing machine. The volume corrections can be calculated by using the general gas law. Software that accomplishes this conversion is available on the T&E computers.

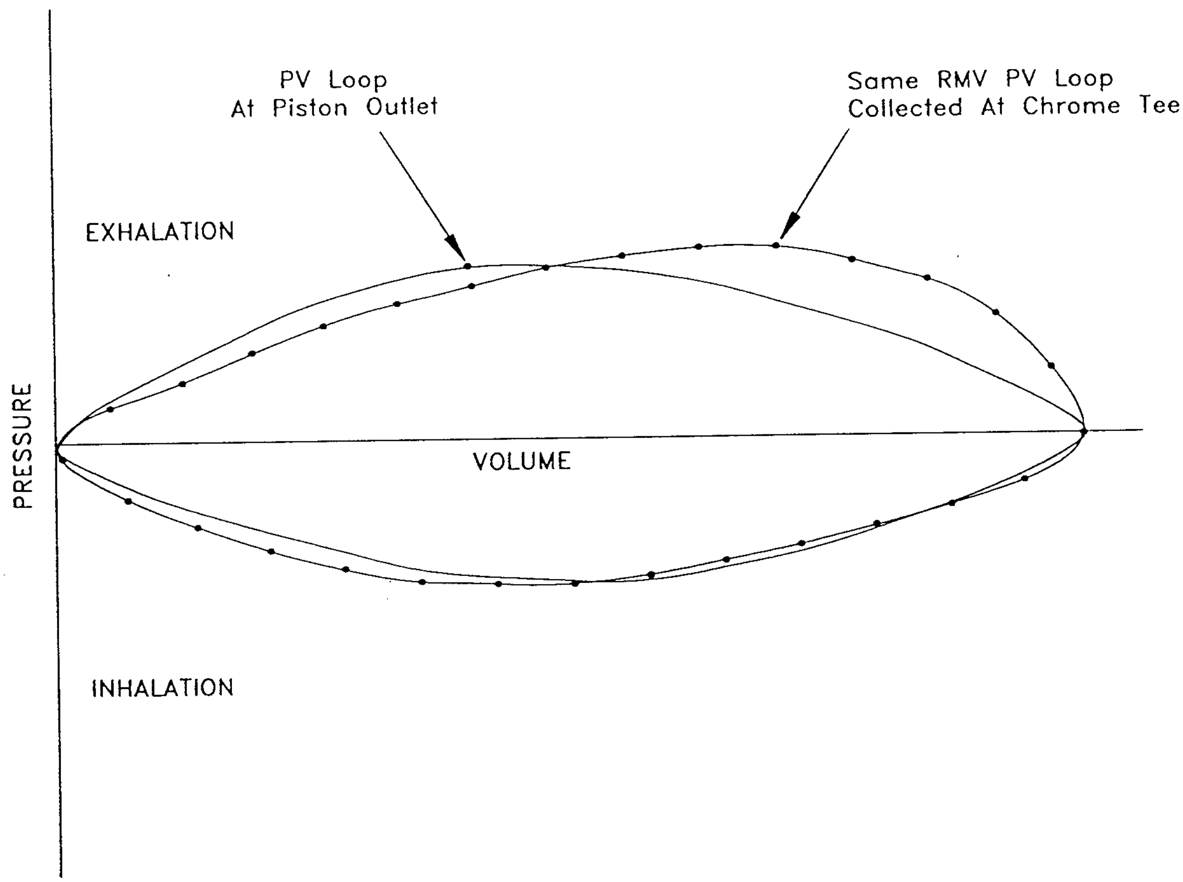


Figure 4-4. Skewed P-V Loop (NEDU Calibration Orifice)

4-6 CO_2 CONTROL CALIBRATIONS

Mass Flow Controller: The Matheson CO_2 mass flow controller output should be checked by timing the flow into a chain compensated Collins 120 liter Tissot Spirometer. The test should be repeated a minimum of 3 times. Insure that the CO_2 regulator pressure is set as specified by the Matheson manual.

Note: Unless the measurement is made quickly, CO_2 will dissolve into the spirometer water, giving a falsely low reading. For example, at equilibrium 1 L of water can contain 0.872 L (STPD) of CO_2 at 1 ATA and 20°C. If CO_2 is in contact with the water only briefly, this error will be minor. The problem can be virtually eliminated by filling the spirometer with a low viscosity fluorocarbon oil, in which CO_2 is poorly soluble.

Mass Spectrometer: Calibrate according to manufacturers' instructions. Record d.c. voltage output at all levels, with at least a zero, mid-range, and span point. All calibration gases must have certificates of compliance on file, with copies of the certificates placed in the daily test log.

4-7 TEST CHAMBER FLOOR PLAN

Test equipment should be configured within the test facility in a standard configuration to allow repeatable test setup, ensuring reliable and repeatable test results. Figure 4-5 is an example of one such NEDU test setup.

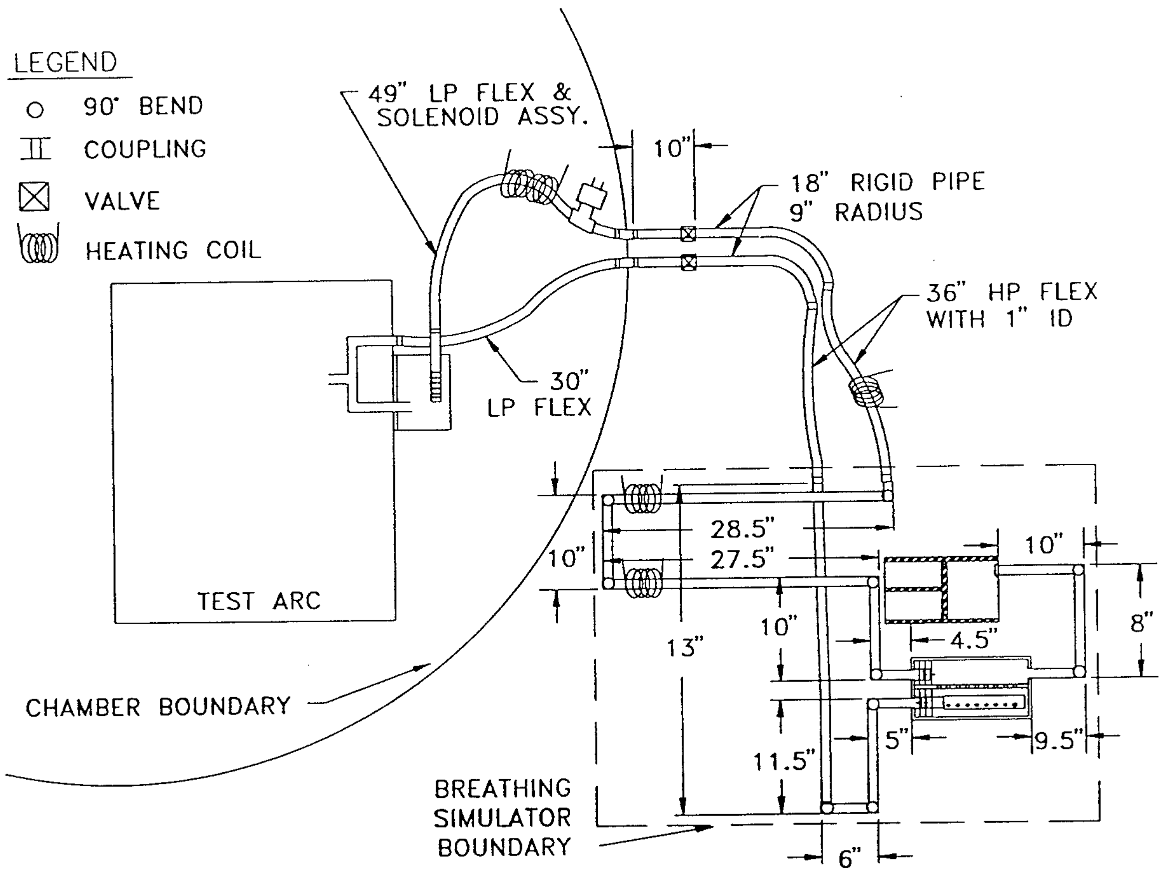


Figure 4-5. Common Test Chamber Floor Plan

4-8 CATEGORY 1 UBA TEST METHODS

4-8.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 1 UBA performance. The results of these tests will be compared to standards set forth for Category 1 UBA performance, Table 3-3, and used in the process of obtaining "Authorized for Navy Use" (ANU) status for the UBA being tested.

4-8.2 Schedule

Category 1 UBA testing requires sufficient time to prepare test setup, conduct tests, perform post test shakedown, cleaning, and disassembly of equipment setup.

4-8.3 Test Equipment (Ref Figure 4-6)

1. Test Article (UBA).

2. EDF Chamber Complex.

3. Water Containment Ark.

4. Breathing Simulator Reimers Consultants, Model No. 1500 or equivalent with humidity addition capabilities.

5. Breathing Air Supply Whip.

6. Breathing Air Supply Gauge, 3D Instruments, 1/4% accuracy and 6-inch face or electronic equivalent.

7. EDF Chamber Depth Gauge, Heise Model 711A or equivalent.

8. Breathing Simulator Piston Position Transducer (LVDT) Longfellow Waters Mfg. Inc., Model No. LF-S-12/300-OB5 or equivalent.

9. Mouth Pressure Transducer, $\pm$1.00 psi wet-wet ΔP transducer mounted as near to suprasternal notch reference as possible. Keller PSI Model 289-540-0001 or equivalent.

10. Pressure Transducer, 200 psid mounted within the test chamber to measure first stage pressure drop. Keller PSI Model 289-540-0200 or equivalent.

11. 80 ft^3 SCUBA tank with a "Y" valve to act as a volume tank allowing a constant pressure supply to the first stage regulator.

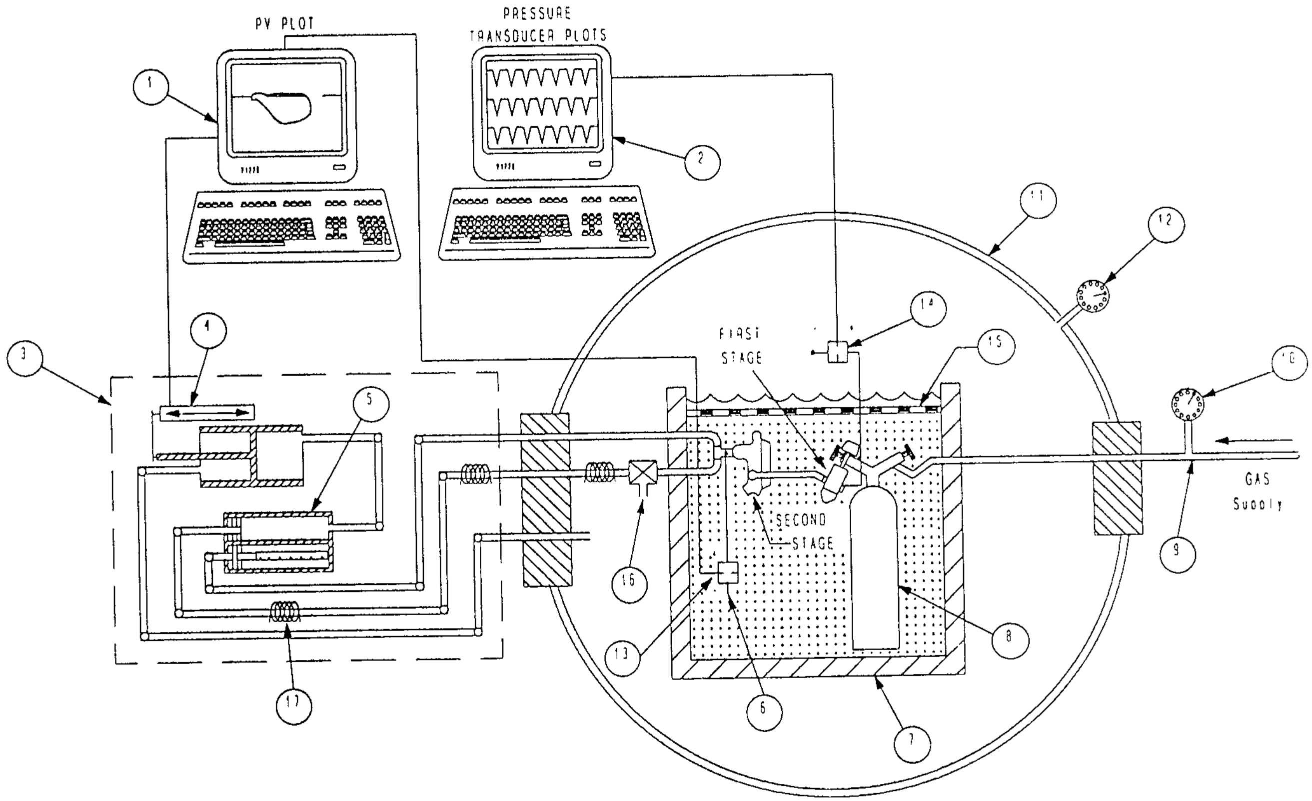
12. Data Acquisition Computer Model 386/486 PC and/or Mac IIci or equivalent with software installed capable of collecting, analyzing and reducing the data at a rate fast enough to capture peaks of any pressure spikes that occur, and display and record data from the transducers. (Reference section 4-2.)

4-8.4 Test Setup

Test equipment shall be configured within the test facility as shown in Figures 4-5 and 4.6. Particular attention must be paid to the hose inner diameter and number of elbows used in the breathing loop. Flow restrictions have been found to be critical and could affect test results significantly.

4-8.4.1 Parameters to be Controlled

1. Breathing simulator settings are given in Table 3.1 and are repeated on the following page for ease of reference.



1. PV Plot
2. Pressure Transducer Plots
3. Breathing Simulator
4. Priston Position Transducer (LVDT)
5. Gas Routing Chamber (Humidity/CO_2 ADD)
6. Suprastermal Notch Reference
7. Water Containment Ark
8. 80 Cu Ft Scuba Tank
9. Supply Line
10. Supply Gauge
11. EDF Chamber Complex
13. Oral Pressure Transducer (Wet Mount)
14. First Stage Over Bottom Pressure Transducer
15. Bubble Defuser
16. Loop Equalizing Solenoid
17. Expired Gas Heater Coil (Typical 3Pl.)
18. Canister Termperature Relay Line

Figure 4-6. Category 1 UBA Test Setup

Table 3.1

BREATHING SIMULATOR SETTINGS

f (BPM)	V_T (Liters)	RMV (L/min)	Diver Work Rate
15	1.5	22.5	Light
20	2.0	40.0	Moderately Heavy
25	2.5	62.5	Heavy
30	2.5	75.0	Severe
30	3.0	90.0	Extreme

2. Exhalation/inhalation time ratio: 1.00/1.00 (all tests).

3. Breathing wave form: sinusoidal (all test).

4. First Stage Air Supply Pressure: 103.42 BAR (1500 psig) and 34.47 BAR (500 psig).

5. Depth Increment Stops: normally 0 to 60.7 msw (0 to 198 fsw) in 10.11 msw (33 fsw) increments or per test plan.

6. Ark water temperature: Ambient or per test plan.

4-8.4.2 Parameters to be Measured

1. Inhalation peak ΔP in kPa.

2. Exhalation peak ΔP in kPa.

3. ΔP vs volume plots (P-V loops).

4. Maximum static O/B pressure at First Stage outlet (Actual O/B).

5. Minimum Dynamic O/B pressure at First Stage outlet (First stage pressure drop).

4-8.4.3 Data to be Computed

1. $\overline{P}_V$ in kPa or J/L.

2. P_{RMS}

3. Total Harmonic Distortion (THD)

4-8.4.4 Data to be Plotted

1. Inhalation and Exhalation ΔP vs depth for each RMV and supply pressure.

2. Pressure vs Volume at each depth, RMV and supply pressure.

3. First stage pressure drop for each depth, RMV and supply pressure.

4-8.5 Test Procedures for Resistive Effort Evaluation

1. a. Ensure that the test article is set to the mid value of the manufacturer's specification, is oriented in the ark per the approved test plan, and is working properly.

   b. Chamber on surface.

   c. Calibrate all transducers.

   d. Perform orifice calibration procedures per 4-3.1.

   e. Open make-up gas supply valve to the test UBA including the "y valve" on the scuba bottle.

   f. Adjust breathing simulator to 22.5 L/min RMV (1.5 liter tidal volume and 15 BPM) per 4-8.4.1, and take data.

   g. Adjust breathing simulator for progressive RMVs per 4-8.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.

   h. Stop breathing simulator.

SAFETY NOTE: **Breathing Simulator should be operating while increasing chamber depth to prevent flooding of equipment.**

2. a. Pressurize chamber to 60.7 msw (198 fsw) in 10.11 msw (33 fsw) increments or per test plan increments. (NOTE: Upon completing all depths and test configurations, go to step 3.)

   b. Repeat steps 4-8.5.1.f through 4-8.5.1.h.

3. a. Bring chamber to surface.

   b. Verify calibration with CLM orifice and on all transducers.

4-8.6 Post Test Shakedown

The test director will verify that all data collected is correct and deliver the compiled test data to the task leader for technical memorandum or report generation.

4-9 CATEGORY 2 UBA TEST METHODS

4-9.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 2 UBA performance. The results of these tests will be compared to standards set forth for Category 2 UBA performance Table 3.3, and used in the process of obtaining Authorized for Navy Use (ANU) status for the UBA being tested.

4-9.2 Schedule

Category 2 UBA testing requires sufficient time to prepare test setup, conduct tests, perform post test shakedown, cleaning, and disassembly of equipment setup.

4-9.3 Test Equipment (Ref Figure 4-7)

1. Test Article (UBA).

2. EDF Chamber Complex.

3. Water Containment Ark.

4. Breathing Simulator, Reimers Consultants, Model No. 1500 or equivalent with humidity and CO_2 add capabilities.

5. HeO_2 Mix or Breathing Air Supply Whips.

6. HeO_2 or Breathing Air Supply Gauge, 3D Instruments 1/4% accuracy, 6-inch face or equivalent.

7. EDF Chamber Depth Gauge, Heise Model 711A or equivalent.

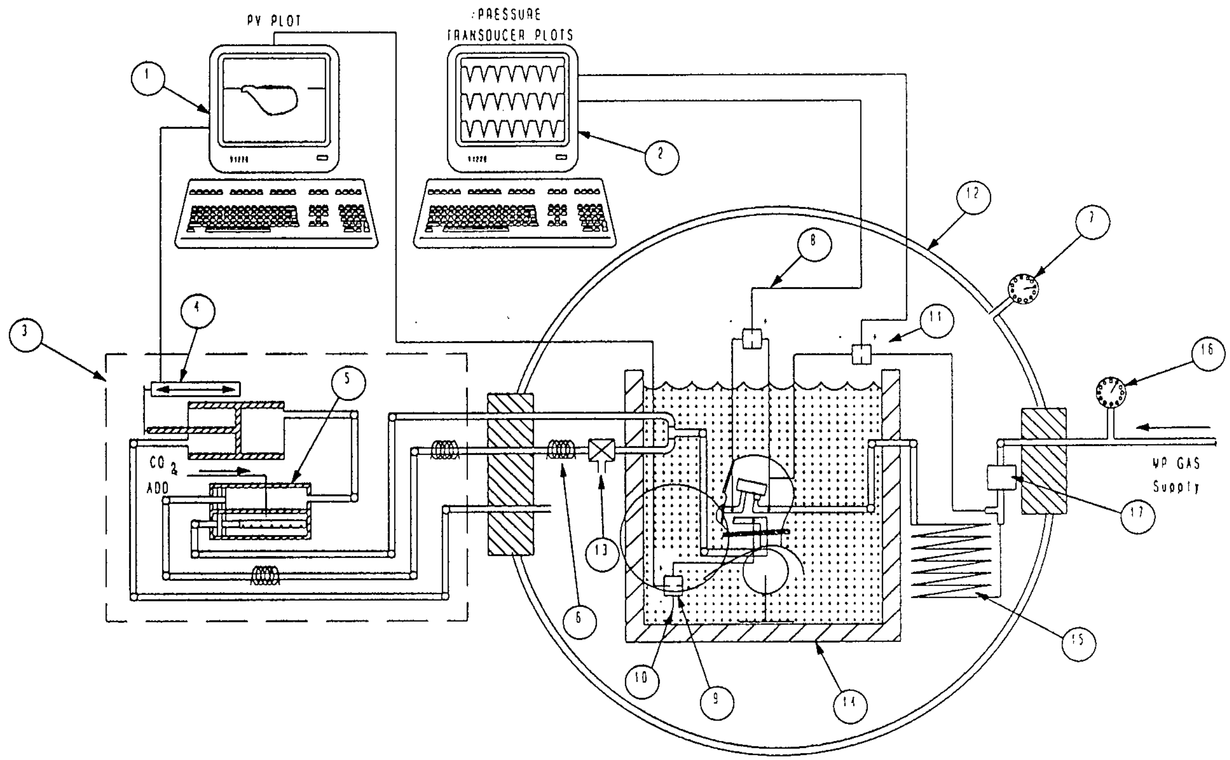
8. Breathing Simulator Piston Position Transducer (LVDT), Longfellow Waters Mfg. Inc. Model No. LF-S-12/300-0B5 or equivalent.

9. Oral Pressure Transducer, $\pm$1.00 psi wet-wet transducer mounted as near to suprasternal notch reference as possible. Keller PSI Model 289-540-0001 or equivalent.

10. Pressure Transducer, 50 psid mounted within the test chamber to measure pressure drop across umbilical. Keller PSI Model 289-540-0050 or equivalent.

11. Pressure Transducer, 50 psid mounted within the test chamber to measure sideblock assembly pressure drop. Keller PSI Model 289-540-0050 or equivalent.

12. Data Acquisition Computer, 386/486 PC and/or Mac IIci or equivalent with software installed capable of collecting, analyzing and reducing the data at a rate fast enough to capture peaks of any pressure spikes that occur and displaying data from the transducers, (Reference Paragraph 4-2).



1. PV Plot
2. Pressure Transducer Plots
3. Breathing Simulator
4. Priston Position Transducer (LVDT)
5. Gas Routing Chamber (Humidity/CO ADD) (Humidity/CO_2 ADD)
6. Expired Gas Heater Coils (Typical 3 PL)
7. Chamber Depth Gauge
8. Sideblock Diff. Pressure Transducer
9. Oral Diff Pressure Transducer [Wet Mount]
10. Ref port to Suprasternal Notch
11. UMB Dif. Pressure Transducer
12. EDF Chamber Complex
13. Loop Equalizing Solenoid
14. Water Containment Ark
15. Drivers Umbilical Supply
16. Supply Gauge
17. Volume Tank

Figure 4-7. Category 2 UBA Test Setup

4-9.4 Test Setup

Test equipment shall be configured within the test facility similar to Figures 4-5 and 4-7. Particular attention must be paid to the inner diameter and number of elbows. These dimensions have been found to be critical and could affect test results.

4-9.4.1 Parameters to be Controlled

1. Breathing simulator settings are given in Table 3.1 and are repeated here for ease of reference.

Table 3.1
BREATHING SIMULATOR SETTINGS

f (BPM)	V_T (Liters)	RMV (L/min)	Diver Work Rate
15	1.5	22.5	Light
20	2.0	40.0	Moderately Heavy
25	2.5	62.5	Heavy
30	2.5	75.0	Severe
30	3.0	90.0	Extreme

2. Exhalation/inhalation time ratio: 1.00/1.00 (all tests).

3. Breathing wave form: sinusoidal (all tests).

4. Divers' gas supply pressure: per test plan.

5. Incremental descent stops: 0 to 60.7 msw (0 to 198 fsw) in 10.1 msw (33 fsw) increments (air breathing resistance test only); 0 to 91.9 msw (0 to 300 fsw) in 10.1 msw (33 fsw) increments, 137.8, 199.1 and 291.0 msw (450, 650, and 950 fsw) if required (HeO_2 breathing resistance tests); or per test plan.

6. Ark water temperature: ambient or per test plan.

4-9.4.2 Parameters to be Measured

1. Inhalation peak ΔP (kPa).
2. Exhalation peak ΔP (kPa).
3. ΔP vs volume plots (P-V loops).
4. Umbilical pressure drop (psid).
5. Sideblock pressure drop (psid).

4-9.4.3 Data to be Computed

1. $\overline{P}_V$ in kPa or J/L.
2. P_{RMS}
3. Total Harmonic Distortion (THD)

4-9.4.4 Data to be Plotted

1. Inhalation and Exhalation ΔP vs depth for each RMV.
2. Pressure vs Volume at each depth and RMV.
3. Umbilical pressure drop at each depth and RMV.
4. Dynamic pressure drop across sideblock assembly at each depth and RMV.

4-9.5 Test Procedures for Resistive Effort Evaluation

1. a. Ensure that the demand regulator is set to the mid value of manufacturer's specifications, is oriented in the ark per the approved test plan, and is working properly.

   b. Chamber on surface.

   c. Calibrate all transducers.

   d. Perform orifice calibration procedures per 4-3.1.

e. Open diver's air supply valve to regulator and set supply pressure per test plan.

f. Adjust breathing simulator to 22.5 L/min RMV (1.5 liters tidal volume and 15 BPM), per 4-9.4.1, and take data.

g. Adjust breathing simulator for progressive RMVs per 4-9.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.

h. Stop breathing simulator.

STOP SAFETY NOTE: **Breathing Simulator should be operating while increasing chamber depth to prevent flooding of equipment.**

2. a. Pressurize chamber from 10.11 msw (33 fsw) to max test depth in 10.11 msw (33 fsw) increments or per test plan increments.

b. Repeat steps 4-9.5.1.f through 4-9.5.1.h.

NOTE: Upon completing all depths and test configurations go to step 3.

3. a. Bring chamber to surface.

b. Verify calibration with CLM orifice and on all transducers.

4-9.6 Post Test Shakedown

The test director will verify that all data collected is correct and deliver the compiled test data to the task leader for technical memorandum or report generation.

4-10 CATEGORY 3 UBA TEST METHODS

4-10.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 3 UBA performance. The results of these tests will be compared to standards set forth for Category 3 UBA performance, Table 3.3 and used in the process of obtaining Authorized for Navy Use (ANU) status for the UBA being tested.

4-10.2 Schedule

Category 3 UBA testing requires sufficient time to prepare test setup, conduct tests, perform post test shakedown, cleaning, and disassembly of equipment setup.

4-10.3 Test Equipment (Ref Figure 4-8)

1. Test Article (UBA).
2. EDF Chamber Complex.
3. Water Containment Ark.
4. Breathing Simulator, Reimers Consultants, Model No. 1500 or equivalent with humidity and CO_2 add capabilities.
5. HeO_2 Mix or Breathing Air Supply Whips.
6. HeO_2 or Breathing Air Supply Gauge, 3D Instruments, 1/4% accuracy, 6-inch face or equivalent.

7. EDF Chamber Depth Gauge, Heise Model 711A or equivalent.

8. Breathing Simulator Piston Position Transducer (LVDT), Longfellow Waters Mfg. Inc. Model LF-S-12/300-0B5 or equivalent.

9. Oral Pressure Transducer, ± 1.00 psi wet-wet ΔP transducer mounted as near to suprasternal notch reference as possible, Keller PSI Model 289-540-0001 or equivalent.

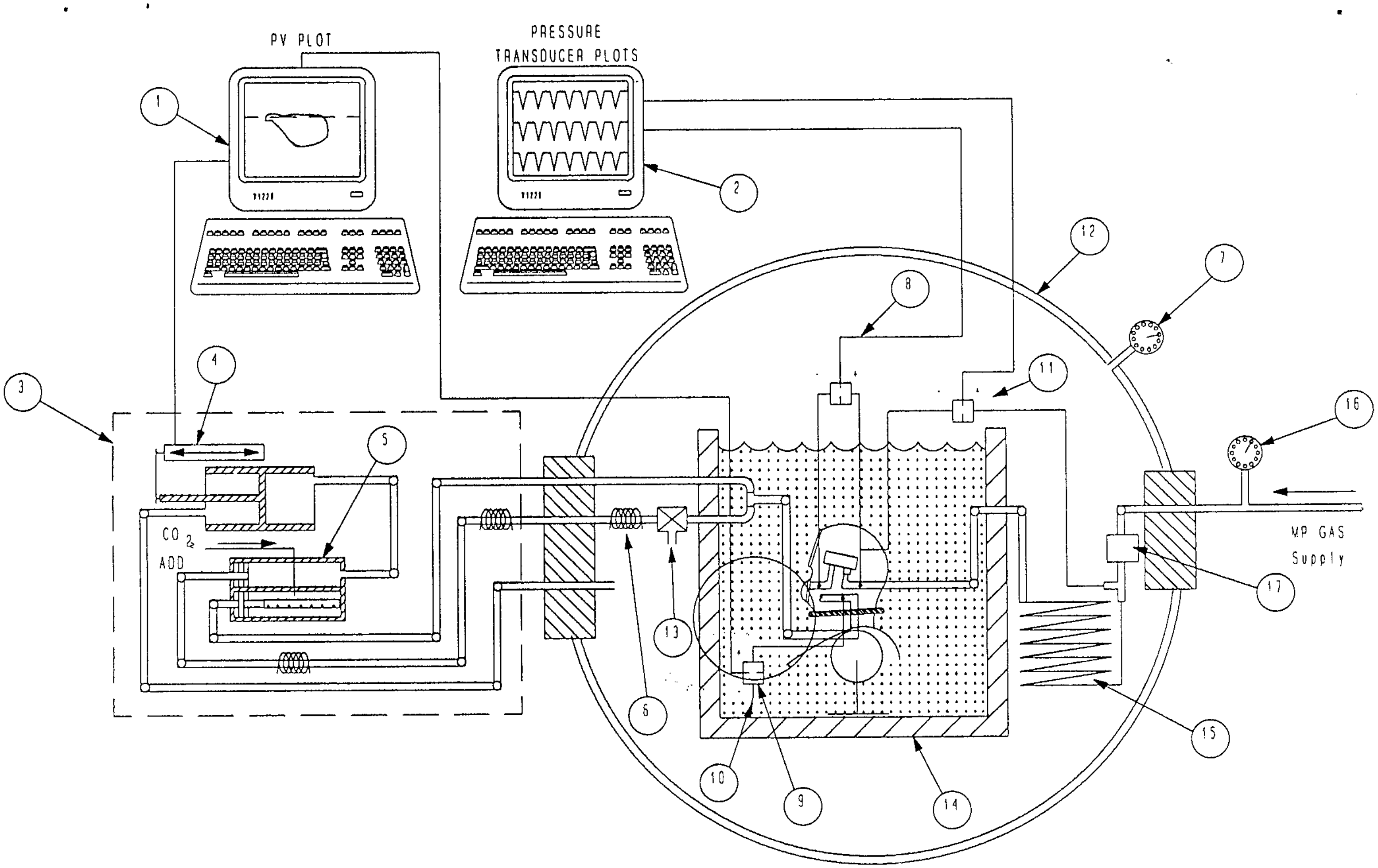
10. Pressure Transducer, 50 psid mounted within the wet chamber to measure pressure drop across umbilical, Keller PSI Model 289-540-0050 or equivalent.

11. Pressure Transducer, 50 psid mounted within the wet chamber to measure umbilical pressure drop, Keller PSI Model 289-540-0050 or equivalent.

12. Data Acquisition Computer, 386/486 PC and/or Mac IIci or equivalent, with software installed capable of collecting, analyzing and reducing the data at a rate fast enough to capture peaks of any pressure spikes that occur and displaying data from the transducers, thermistors and gas analyzers (Reference Paragraph 4-2).

4-10.4 Test Setup

Test equipment shall be configured within the test facility similar to Figures 4-5 and 4-8, paying particular attention to flow restrictions.



1. PV Plot
2. Pressure Transducer Plots
3. Breathing Simulator
4. Priston Position Transducer (LVDT)
5. Gas Routing Chamber (Humidity/CO_2 ADD)
6. Expired Gas Heater Coils (Typical 3 PL)
7. Loop Equalizing Solenoid
8. Water Containment Ark
9. Divers Umbilical Supply
10. Supply Gauge
11. Chamber Depth Gauge
12. EDF Chamber Complex
13. Volume Task
14. Oral Diff. Pressure Transducer (Wet Mount)
15. Ref. Port to Suprasteral Notch
16. Umb. Diff. Pressure Transducer
17. LFE Diff. Pressure Transducer
18. Laminar Flow Element (with proper upstream and downstream straight pipe)

Figure 4-8. Category 3 UBA Test Setup

4-10.4.1 Parameters to be Controlled

1. Breathing simulator settings are given in Table 3.1 and are repeated here for ease of reference.

Table 3.1
BREATHING SIMULATOR SETTINGS

f (BPM)	V_T (Liters)	RMV (L/min)	Diver Work Rate
15	1.5	22.5	Light
20	2.0	40.0	Moderately Heavy
25	2.5	62.5	Heavy
30	2.5	75.0	Severe
30	3.0	90.0	Extreme

2. Exhalation/inhalation time ratio: 1.00/1.00 (all tests).

3. Breathing wave form: sinusoidal (all test).

4. Divers gas supply pressure: per test plan.

5. Incremental descent stops: 0 to 60.7 msw (0 to 198 fsw) in 10.1 msw (33 fsw) increments (air breathing resistance test only); 0 to 91.9 msw (0 to 300 fsw) in 10.1 msw (33 fsw) increments (HeO_2 breathing resistance tests only) or per test plan.

6. Ark water temperature: ambient or per test plan.

4-10.4.2 Parameters to be Measured

1. Inhalation peak ΔP (kPa).
2. Exhalation peak ΔP (kPa).
3. Umbilical pressure drop in psid.
4. Helmet pressure drop in psid.
5. If required, Laminar flow element (LFE) pressure drop in psid.

4-10.4.3 Data to be Computed

1. $\overline{P}_V$ in kPa or J/L.
2. P_{RMS}
3. Total Harmonic Distortion (THD)
4. If required, flow delivered to helmet (ACFM), from LFE data.

4-10.4.4 Data to be Plotted

1. Inhalation pressure at each depth and RMV.
2. Exhalation pressure at each depth and RMV.
3. Pressure vs volume at each depth and RMV.
4. Umbilical pressure drop at each depth and RMV.
5. Flow at each depth and RMV.
6. Dynamic pressure drop across helmet supply valve assembly at each depth and RMV.

4-10.5 Test Procedures for Breathing Resistance Evaluation

1. a. Ensure that the helmet is set up to manufacturer's specifications, is oriented in the ark per the approved test plan, and is working properly.
   b. Chamber on surface.
   c. Calibrate all transducers.

d. Perform orifice calibration procedures, per 4-3.1.

e. Open diver's air supply valve to regulator and set supply pressure at 11.38 BAR (165 psig) over bottom or per test plan.

f. Adjust breathing simulator to 22.5 L/min RMV (1.5 liters tidal volume and 15 BPM) per 4-10.4.1 and take data.

g. Adjust breathing simulator for progressive RMVs per 4-10.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.

h. Stop breathing simulator.

STOP **SAFETY NOTE: Breathing Simulator must be operating while increasing chamber depth to prevent flooding of equipment.**

2. a. Pressurize chamber from 10.1 msw (33 fsw) to 60.7 msw (198 fsw) in 10.1 msw (33 fsw) increments for air breathing test or per test plan and repeat steps 4-10.5.1.f through 4-10.5.1.h.

b. Pressurize chamber from 10.1 msw (33 fsw) to 91.9 msw (300 fsw) in 10.1 msw (33 fsw) increments for HeO_2 breathing test or per test plan and repeat steps 4-10.5.1.f through 4-10.5.1.h.

NOTE: Upon completing all depths and test configuration go to step 3.

3. a. Bring chamber to surface.

b. Verify calibration with CLM orifice and on all transducers.

4-10.6 Post Test Shakedown

The test director will verify that all data collected is correct and deliver the compiled test data to the task leader for report and/or technical memorandum generation.

4-11 CATEGORY 4 UBA TEST METHODS

4-11.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 4 UBA performance. The results of these tests will be compared to standards set forth for Category 4 UBA performance, Table 3.3, and will be used in the process of obtaining Authorized for Navy Use (ANU) status for the UBA being tested.

4-11.2 Schedule

Category 4 UBA testing requires sufficient time to prepare test setup, conduct tests, perform post test shakedown, cleaning, and disassembly of equipment setup.

4-11.3 Test Equipment (Ref Figure 4-9)

1. Test Article (UBA).
2. EDF Chamber Complex.
3. Water Containment Ark.
4. EDF Heating and Cooling System capable of controlling ark water temperature $\pm 2°F$ during the canister duration tests (29° - 90°F).
5. Breathing Simulator, Reimers Consultants Model No. 1500 or equivalent with humidity and CO_2 add capabilities.
6. HeO_2 Mix and 100% O_2 Supply Whip. (If UBA gas bottles not used).
7. HeO_2 and 100% O_2 Supply Gauge, 3D Instruments, 6-inch face and 1/4% accuracy.
8. EDF Chamber Depth Gauge, Heise Model 711A or equivalent.
9. Breathing Simulator Piston Position Transducer (LVDT), Longfellow Waters Mfg. Inc. Model No. LF-S-12/300-0B5 or equivalent.
10. Oral Pressure Transducer, ± 1.00 psi wet-wet ΔP transducer mounted as near to suprasternal notch reference as possible. Keller PSI Model 289-540-0001 or equivalent.

11. CO_2 Gas Analyzer, Rosemount/Beckman Industrial Model 880 or equivalent, capable of continuous monitoring of gas sample and providing proportional input to the data acquisition computer.

12. O_2 Gas Analyzer, Rosemount/Beckman Industrial Model 755A or equivalent, capable of continuously monitoring O_2 levels in the breathing loop and providing proportional input to the data acquisition computer.

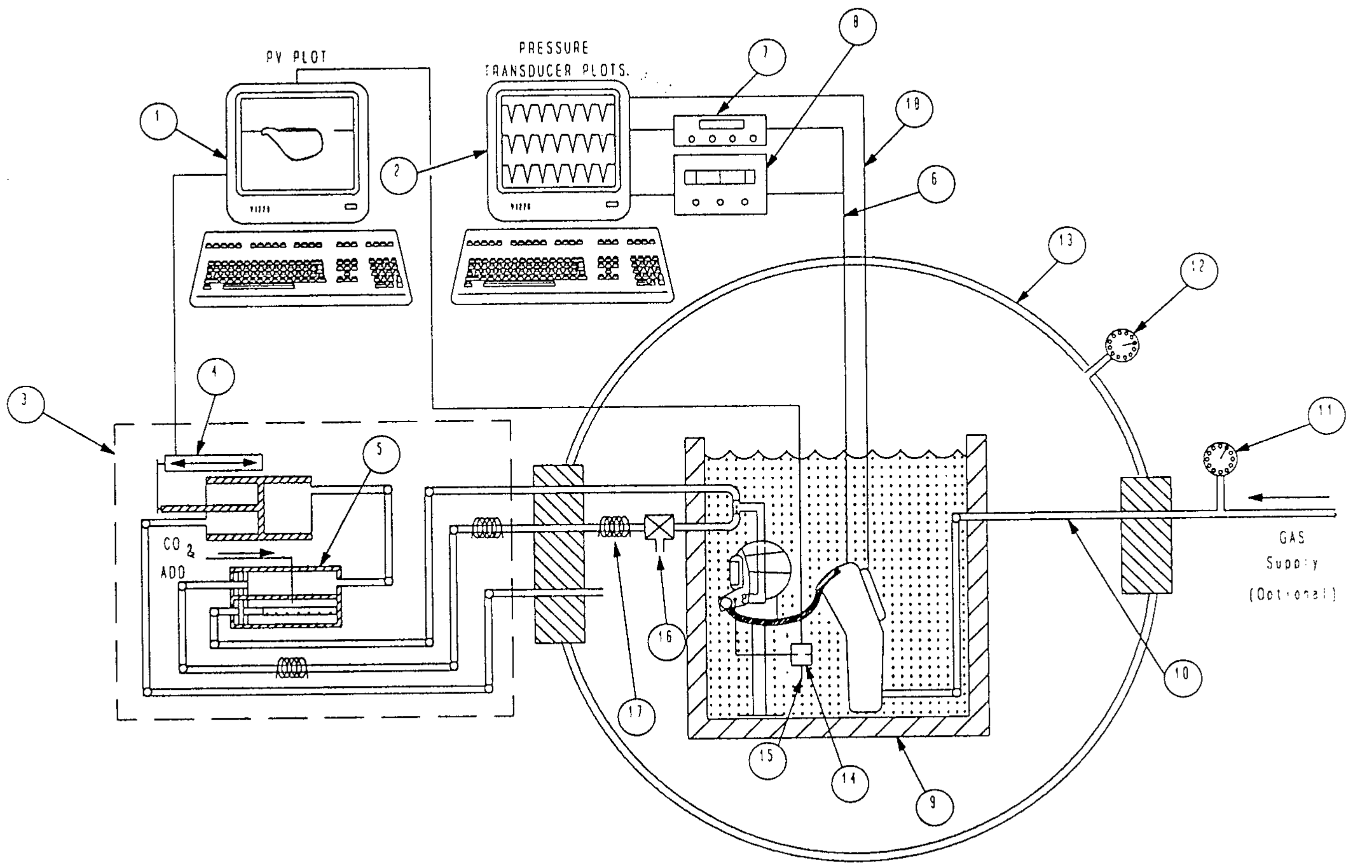
NOTE: If O_2 set point and/or breath by breath analysis is desired a mass spectrometer must be used to attain the required response time.

13. Data Acquisition Computer, 386/486 PC and/or Mac IIci or equivalent with software installed capable of collecting, analyzing and reducing the data at a rate fast enough to capture peaks of any pressure spikes that occur and displaying data from the transducers (Reference Paragraph 4-2).

14. Electroscale to measure weight of CO_2 expended from cylinder (Canister Duration Study).

15. Vacuum Heating Oven (Canister Duration Study).

16. Matheson model 8272-0423 mass flow controller, or equivalent, to control CO_2 injection rate during canister durations.



1. PV Plot
2. Canister Temp Gas Analysis Readout
3. Breathing Simulator
4. Priston Position Transducer (LVDT)
5. Gas Routing Chamber (Humidity/CO_2 ADD)
6. O_2 and CO_2 Sampling Lin
7. O_2 Analyzer
8. CO_2 Analyzer
9. Water Containment Ark
11. HP Supply Whip
12. HP Supply Gauge
13. EDF Chamber Complex
14. Oral Pressure Transducer (Wet Mount)
15. Ref. Port to Suprasteral Notch
16. Loop Equalizing Solenoid
17. Expired Gas Heater Coil (Typical 3Pl.)
18. Canister Termperature Relay Line

Figure 4-9. Category 4 UBA Test Setup

4-11.4 Test Setup

Test equipment shall be configured within the test facility similar to Figures 4-5 and 4-9 paying particular attention to flow restrictions.

4-11.4.1 Parameters to be Controlled

1. Breathing simulator settings are given in Table 3.1 and are repeated here for ease of reference.

Table 3.1
BREATHING SIMULATOR SETTINGS

f (BPM)	V_T (Liters)	RMV (L/min)	Diver Work Rate
15	1.5	22.5	Light
20	2.0	40.0	Moderately Heavy
25	2.5	62.5	Heavy
30	2.5	75.0	Severe
30	3.0	90.0	Extreme

2. Exhalation/inhalation time ratio: 1.00/1.00 (all tests).

3. Breathing wave form: sinusoidal (all tests).

4. Canister duration: test to be conducted to maximum apparatus operating depth using absorbent material being tested at water temperatures of -1.7, 4.4, 21.1 and 32.2° C (29, 40, 70 and 90°F) or per test plan.

5. Incremental descent stops: 0 to 60.7 msw (0 to 198 fsw) in 10.1 msw (33 fsw) increments (air breathing resistance test only); 0 to 91.9 msw (0 to 300 fsw) in 10.1 msw (33 fsw) increments (HeO_2 breathing resistance tests only); 10.1, 20.2, 30.3 and 50.5 msw (33, 66, 99 and 165 fsw) (air/O_2 consumption tests only); 15.3, 30.6, 45.9, 61.3 and 91.9 msw (50, 100, 150, 200 and 300 fsw) (HeO_2/O_2 consumption tests only) or per test plan.

6. Exhaled gas temperature on canister duration tests.

NOTE: Both inhale and exhale gas temperature are measured at the Collins Chrome T, just downstream and upstream respectively of the routing valves.

8. Depths for canister duration tests:

   a. Air: per test plan.

   b. HeO_2: per test plan.

9. CO_2 injection for canister duration test (Refer to section 3-5).

   a. 2.0 L/min CO_2 at 50 L/min RMV

   b. 0.9 L/min CO_2 at 22.5 L/min RMV

10. Diluent: Air & HeO_2 (84/16) @ 68.95 BAR (1000 psig) supply pressure or per test plan.

NOTE: 100% O_2 will be plumbed to the O_2 side of the UBA gas addition system at 68.95 BAR (1000 psig) supply pressure or UBA's O_2 bottle will be used.

4-11.4.2 Parameters to be Measured

1. Mouth ΔP in kPa.

2. CO_2 level out of scrubber in % SEV (kPa). (canister duration tests only).

3. O_2 level in inhalation hose during O_2 consumption tests (%).

4. Visual verification of breathing simulator exhaled gas relative humidity (canister duration tests only).

5. Breathing simulator exhaled gas temperature in °F (canister duration tests only).

4-11.4.3 Data to be Computed

1. $\overline{P}_V$ in kPa or J/L.

2. P_{RMS}

3. Total Harmonic Distortion (THD)

4-11.4.4 Data to be Plotted

1. Inhalation pressure at each depth and RMV determined from the line connecting the points of no flow (breathing resistance test only).

2. Exhalation pressure at each depth and RMV determined from the line connecting the points of no flow (breathing resistance test only).

3. Pressure vs Volume at various depths depending upon the UBA's operational limits at constant RMV and supply pressure (breathing resistance tests only).

4. Mouth differential pressure (kPa) vs time (canister duration only).

5. CO_2 out of scrubber (% SEV, kPa) vs time (canister duration tests only).

6. Po_2 in inhalation gas (% SEV, kPa) vs time (O_2 consumption tests only).

4-11.5 Test Procedures

4-11.5.1 Test Plan for Breathing Effort Evaluation

1. The test procedures are as follows:

    a. Ensure that the test article is set to the midpoint of manufacturer's specifications, is oriented in the ark per the approved test plan, and is working properly.

    b. Chamber on surface.

    c. Calibrate all transducers and temperature probes.

    d. Perform orifice calibration procedure per 4-3.1.

    e. Open make-up gas supply valve to test UBA.

    f. Adjust breathing simulator to 22.5 L/min RMV (1.5 liter tidal volume and 15 BPM) per 4-11.4.1 and take readings.

    g. Adjust breathing simulator for progressive RMVs per 4-11.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.

    h. Stop breathing simulator.

SAFETY NOTE: **Breathing Simulator must be operating while increasing chamber depth to prevent flooding of equipment.**

2. a. Pressurize chamber from 10.1 msw to 50.5 msw (33 fsw to 165 fsw) in 10.1 msw (33 fsw) increments or per test plan and repeat steps 4-11.5.1.f through 4-11.5.1.h.

b. Pressurize chamber from 10.1 msw to 91.9 msw (33 fsw to 300 fsw) in 10.1 msw (33 fsw) increments for HeO_2 breathing test, or per test plan, and after HEO_2 breathing test, repeat steps 4-11.5.1.f through 4-11.5.1.h.

NOTE: Upon completing all depths and test configurations go to step 3.

3. a. Bring chamber to surface.

b. Verify calibration with CLM orifice and on all transducers.

4-11.5.2 Canister Duration Tests

4-11.5.2.1 Canister Breakthrough Time

1. Rationale.

The most direct way to determine canister duration is by measuring the time to canister breakthrough using a continuous CO_2 injection rate. Duration is primarily dependent on $\dot{V}co_2$, CO_2 injection rate, temperature, and to a lesser extent, RMV. Canister efficiency drops at low temperature and high RMV.

2. Parameters to be controlled: Exhalation/inhalation time ratio: 1.00/1.00 (all tests). Breathing wave form: sinusoidal (all tests).

3. Method

a. Fill UBA canister with absorbent (within predetermined fill volume and weight ranges). Ensure UBA is within factory specifications for operation.

b. Chamber is on the surface with UBA immersed in water at the test temperature.

c. Calibrate all transducers, CO_2 analyzer, CO_2 flowmeters, and temperature

probes.

d. Open make-up supply valve.

e. Start humidity add system.

f. Pressurize chamber: per test plan

g. Start CO_2 addition and maintain as indicated below until 2.0% SEV CO_2 is reached. Complete a minimum of 5 runs for the two injection rates given below. Additional runs may be required depending on the consistency of canister performance.

   (1) 2.0 liters per minute (L/min) CO_2 at 50 L/min RMV - (Tidal Volume 2.0 L, Frequency 25 BPM) at 1.67, 4.4, 21.1, and 32.2°C (29°, 40°, 70° and 90°F), or per test plan.

   (2) 0.9 L/min CO_2 at 22.5 L/min RMV - (Tidal Volume 1.5 L, Frequency 15.0 BPM) at above temperatures.

h. Record canister effluent CO_2 level from Beckman CO_2 analyzer at least every 20 seconds until 2% SEV CO_2 limit is reached.

4-11.5.2.2 Canister Absorption Capacity

1. Rationale

The volume of CO_2 gas (at STPD) absorbed by a UBA canister under a particular set of conditions can be calculated based on the CO_2 injection rate. A canister efficiency can also be reported using this volume as the percentage of the ideal maximum CO_2 volume (at STPD) that the absorbent can theoretically remove. The limitation to this approach is that canister efficiency and the amount of CO_2 absorbed is not constant. It is dependent on both temperature and RMV.

2. Method

a. Conduct canister absorption capacity testing per 4-11.5.2.1.

b. Multiply the time in minutes to reach the 0.5 % and 2.0% SEV CO_2 levels by the CO_2 injection rate (liters per minute). From this number, subtract the volume of CO_2 removed by the analyzer for sampling before the 0.5 % SEV CO_2 limits are reached.

c. Repeat above calculations following each of the runs at each temperature condition.

d. Calculate efficiency for each run. This efficiency calculation uses the dry unreacted mass of an absorbent required to fill the canister and the volume (liters at STP) that was put through the canister prior to breakthrough.

$$E_V = (V_{abs} \cdot Aw \cdot 100)/(Ms \cdot 22.4 \text{ L/mole})$$

where:

E_V	=	percent absorption efficiency by CO_2 injection rate method.
V_{abs}	=	volume of CO_2 absorbed liters (at STPD) determined by multiplying the time to reach a particular canister effluent CO_2 level (minutes) by the injection rate (liters per minute) and then subtracting the volume of CO_2 removed by the analyzer in sampling.
Aw	=	Gram weight of absorbent required to absorb one mole of carbon dioxide.
Ms	=	dry mass of the unreacted absorbent. Determined by drying an equivalent volume of absorbent used in the UBA canister in a vacuum oven at 150° C for 6 hours.

In practice, the percentage of Ms available to react with CO_2 depends on granule size, porosity, and hydration. Thus efficiency as calculated above is of limited utility in comparing different absorbents.

4-11.5.2.3 Mouth Differential Pressure

1. Rationale

A product of the reaction of CO_2 with the absorbent material is water. As water collects in the canister bed during extended use, an additional impedance to air flow may be introduced. This impedance to flow may increase the overall UBA breathing resistance. This differential pressure will be measured during the course of canister capacity testing to verify if

a significant increase is occurring during canister usage.

2. Method

Plot mouth differential pressure referenced to the suprasternal notch as a function of time during the canister absorption study. Watch for any increase in the differential pressure that will add to the overall mouth differential pressure.

4-11.5.3 CO_2 Injection Methods

The CO_2 injection system at NEDU incorporates the use of a Matheson model 8272-0423 mass flowmeter for controlling the gas flow into the UBA during tests. The weight change of the high pressure cylinder containing the CO_2 is also measured continuously using a digital scale as additional verification of the proper injection rate of CO_2 during the test. The mass flowmeter must be calibrated prior to each dive series for the specific rate of flow using a Collins chain compensated gasometer. The measured volume is corrected to STPD. Some manufacturers calibrate their mass flowmeters at 70° F so a correction must be made to achieve the STPD standard. As stated above, the time weight course of change of the high pressure CO_2 cylinder is monitored as a secondary check. The calculation of average CO_2 injection rates using the weight loss of the CO_2 supply cylinder is accomplished as follows:

a. Net weight of CO_2 used in ounces (starting weight - ending weight) divided by 0.0696 equals total CO_2 used in liters.

b. Liters of CO_2 used divided by total minutes of test equals average CO_2 injection in L/min.

$$\textit{Average } CO_2 \textit{ injection rate} = \frac{\textit{Wt of } CO_2(oz) \textit{ injected during test}}{(0.0696)\ x\ (\textit{total test time } \mathrm{min})}$$

4-11.5.4 O_2 Consumption/Control System Evaluation

1. Rationale

The O_2 consumption test is designed to analyze the ability of a UBA oxygen control system to maintain a constant partial pressure of O_2 within the UBA. The following are general rules that the experienced operator should follow when setting up and conducting an O_2 consumption simulation on a closed-circuit UBA:

a. O_2 is "consumed" out of the UBA inhalation hose prior to entering the exhale bag or canister. Gas flows through a 0.9525 cm (3/8-inch) OD tubing from the UBA through the chamber penetrator and to the O_2 consumption simulator

(Figure 4-10).

b. Inert gas is added back into the system at the breathing machine bubble chamber via 0.3175 cm (1/8-inch) HP tubing from the O_2 consumption simulator.

In the event that a depth, work rate, or O_2 set point other than that described in Table 3.2 is required, the following formulas provide a method for calculating the various mixed gas out and inert gas add flow rates required for simulation.

Example 1: Calculate mix out and inert added at 18.29 msw (60 fsw) (2.82 ATA) and 0.7 ATA

$$\%O_2 \text{ within mix} = \frac{0.70ATA}{2.82ATA} = 0.248 = 24.8\%$$

$$Mixout = \frac{\%O_2 \text{ consumed } (L/\text{min})}{\%O_2 \text{ within mix}}$$

Inert gas addition is equal to the mix out minus the O_2 consumed at 18.29 msw (60 fsw) as calculated for a resting diver.

Inert added = mix out - O_2 consumed

Inert added = 2.58 L/min - 0.64 L/min =1.94 L/min

Table 3-2 SUMMARY TABLE OF REQUIRED FLOW RATES

Depth (fsw)	Rest Mix Out/Inert Add	Work Mix Out/Inert Add
9.2 (30)	1.75/1.61	4.09/3.09
15.3 (50)	2.30.2.16	5.39/4.39
30.6 (100)	3.68/3.54	8.64/7.64
45.9 (150)	5.07/4.93	11.88/10.88
61.3 (200)	6.46/6.32	15.13/14.13
91.9 (300)	9.23/9.09	21.62/20.62
153.2 (500)	14.77/14.63	34.61/33.61
214.4 (700)	20.31/20.17	47.59/46.59
245.1 (740)	21.41/21.27	50.19/49.19
245.1 (800)	23.08/22.94	54.09/53.09
306.3 (1000)	28.62/28.48	67.08/66.08

NOTE: 0.5 L/min must be added to all inert addition levels to compensate for the O_2 gas analysis sample from the UBA to the gas analyzer. *This amount should be verified for the specific O_2 analyzer being used.* Table 3.2 has the 0.5 L/min already added.

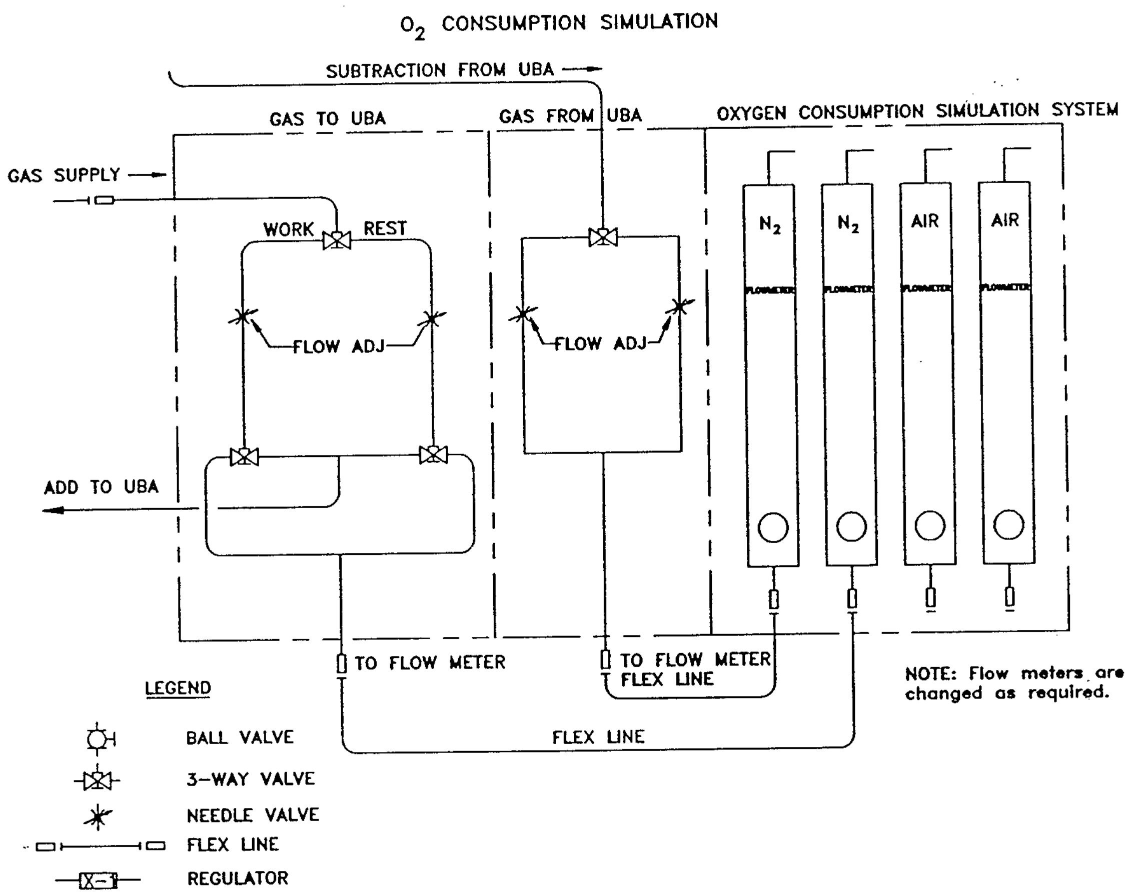


Figure 4-10. O_2 Consumption Simulator

2. Instrumentation setup for O_2 consumption study (Reference Figure 4-10.):

a. Oral ΔP pressure transducer $\pm$ 6.895 kPa ($\pm$ 1.0 psi) (Keller PSI Model 289-540-0001 or equivalent)

b. 1379 kPa (200 psig) O_2 pressure transducer, used to determine when UBA adds O_2 (Keller PSI Model 289-540-0200 or equivalent)

c. Computer graphic recording of: oral ΔP, $\%O_2$ in inspired gas and O_2 add valve firings

d. Breathing simulator settings: same as Category 1 (Table 3.1)

e. Exhalation/inhalation time ratio: 1.00/1.00

f. Breathing wave form: sinusoidal

g. Gas supply:

Air:	0-60.7 msw (0-198 fsw)
HeO_2:	84/16 @ 0-91.9 msw (0-300 fsw)
	95/5 @ 91.9-306.3 msw (300-1000 fsw)
	98/2 @ 306.3-490.1 msw (1000-1600 fsw)

h. Increment descent stops according to mission of rig:
(1.) 0 to 60.7 msw (0 to 198 fsw) in 10.1 msw (33 fsw) increments on air or per test plan
(2.) 0 to 91.9 msw (0 to 300 fsw) in 15.3 msw (50 fsw) increments, 91.9 to 490.1 msw (300 to 1600 fsw) in 61.3 msw (200 fsw) increments on HeO_2 or per test plan

i. Water temp: ambient unless otherwise specified

j. O_2 consumption simulation tests (Table 4.3)

k. Results of test:

O_2 inspired (Po_2 ATA) vs time (min)

O_2 valve firing vs time (min) at each depth msw (fsw) and RMV

Table 4-3. O_2 CONSUMPTION TEST CONDITIONS

Duration (Min)	**$\dot{V}O_2$ L/min STPD**	**RMV L/min**	**V_T (Liters)**	**Frequency (BPM)**	**Diver Effort**
4	0.64	22.5	1.5	15.0	Resting
6	1.50	50.0	2.0	25.0	Working

3. Test Plan

a. Ensure that test article is set to factory specifications and is working properly.

b. Chamber on surface.

c. Calibrate all transducers and O_2 analyzer.

d. Perform orifice calibration procedures, per 4-3.1.

e. Open make-up gas supply valve to test UBA (diluent: Air)

f. Water temperature to be 21.1°C (70°F) or per test plan.

g. Press chamber to 10.1 msw (33 fsw) at a rate as close to 18.29 MPM (60 FPM) as possible.

h. Start CO_2 add system with the normal rest/work cycles or continuous injection rate.

i. Start O_2 consumption system, when chamber reaches the bottom, in cycle with the CO_2 add system.

j. Take data continuously for 10 minutes for each RMV setting in Table 3.1 or per approved test plan.

k. Bring chamber to the surface.

l. Verify calibration with CLM Orifice and on all transducers.

4. Repeat steps 4-11.5.4.3.h through 4-11.4.5.3.j at 20.2, 30.3, and 50.5 msw (66, 99 and 165 fsw) or per test plan.

5. If appropriate, repeat steps 4-11.5.4.3.h through 4-11.5.4.3.j except using HeO_2 as a diluent and take data at 15.3, 30.6, 45.9, 60.96 and 91.9 msw (50, 100, 150, 200 and 300 fsw) or per test plan.

4-11.6 Post Test Shakedown

The test director will verify that all data collected is correct and deliver the compiled test data to the task leader for technical memorandum or report generation.

4-12 CATEGORY 5 UBA TEST METHODS

4-12.1 Introduction

The purpose of these test procedures is to establish a standardized method to evaluate Category 5 UBA performance. The results of these tests will be compared to standards set forth for Category 5 UBA performance, Table 3.3 and used in the process of obtaining Authorized for Navy Use (ANU) status for the UBA being tested.

4-12.2 Schedule

Category 5 UBA testing requires sufficient time to prepare test setup, conduct tests, perform post test shakedown, cleaning, and disassembly of equipment setup.

4-12.3 Test Equipment (Ref Figure 4-11)

1. Test Article (UBA)

2. EDF Chamber Complex

3. Water Containment Ark

4. EDF Heating and Cooling System capable of controlling ark water temperature $\pm$ 0.035°C ($\pm$ 2°F) during the canister duration tests -1.67 to 32.2°C (29°-90°F).

5. Breathing Simulator, Reimers consultants Model No. 1500 or equivalent with humidity and CO_2 add capabilities.

6. HeO_2 Mix and 100% O_2 Supply Whip.

7. HeO_2 and 100% O_2 Supply Gauge, 3D Industries, with 6-inch face and 1/4% accuracy.

8. EDF Chamber Depth Gauge, Heise Model 711A or equivalent.

9. Breathing Simulator Piston Position Transducer (LVDT), Longfellow Waters Mfg. Inc. Model No. LF-S-12/300-OB or equivalent.

10. Oral Pressure Transducer, $\pm$ 6.985 kPa ($\pm$ 1.00 psi) wet-wet ΔP transducer mounted as near to suprasternal notch reference as possible, Keller PSI Model 289-540-0001 or equivalent.

11. Pressure Transducer, 1379 kPa (200 psig) to measure pressure drop across umbilical, Keller PSI Model 289-540-0200 or equivalent.

12. CO_2 Gas Analyzer, Rosemount/Beckman Industrial Model 880 or equivalent, capable of continuous monitoring of gas sample and providing proportional input to the data acquisition computer.

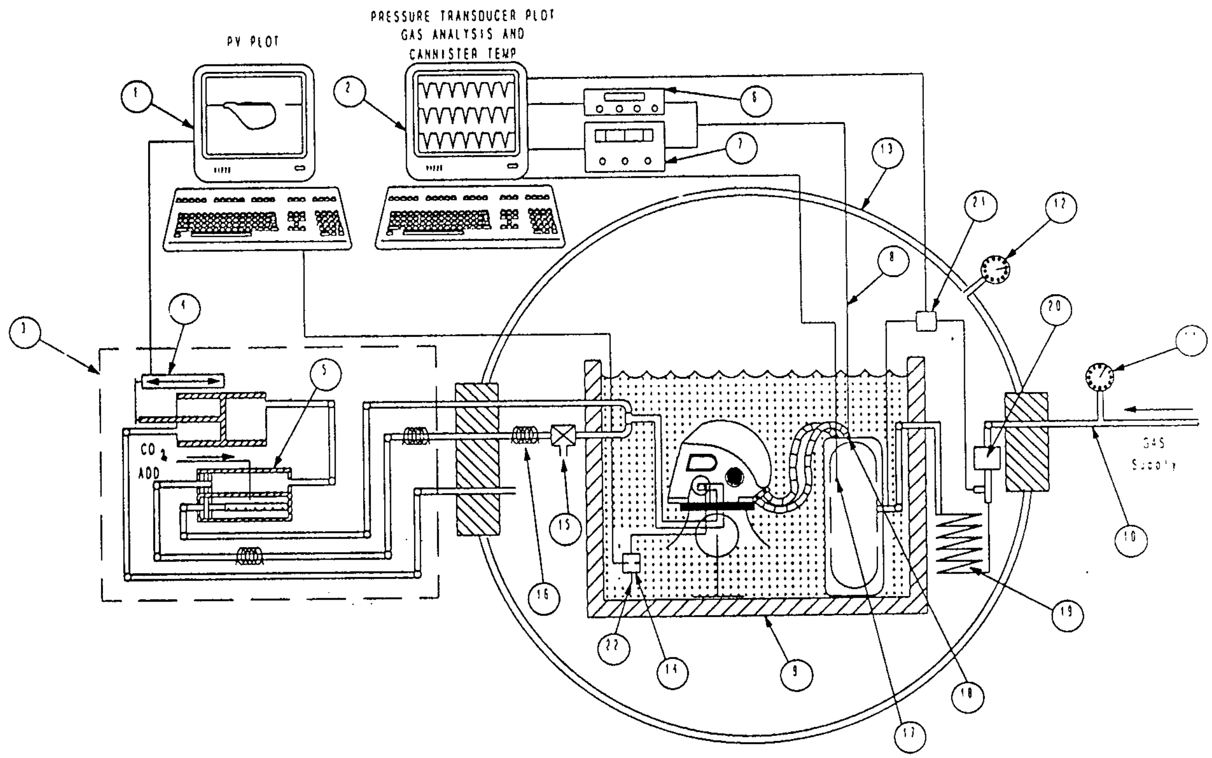
13. O_2 Gas Analyzer, Rosemount/Beckman Industrial Model 755A or equivalent, capable of continuously monitoring O_2 levels in the breathing loop and providing input to the data acquisition computer.

14. Data Acquisition Computer Model 386/486 PC and/or Mac IIci or equivalent with software installed capable of collecting, analyzing and reducing the data at a rate fast enough to capture peaks of any pressure spikes that might occur and displaying data from the transducers. (Reference Paragraph 4-2.)

15. Electroscale to measure weight of CO_2 expended from cylinder (Canister Duration Study).

16. Vacuum Heating Oven (Canister Duration Study).

17. Matheson mass flow controller model 8272-0423 or equivalent for controlling the CO_2 injected during a canister duration study.



1. PV Plot
2. Pressure Transducer Plot, Gas Analysis and Canister Temp
3. Breathing Simulator
4. Piston Position Transducer
5. Gas Routing Chamber (Humidity/CO_2 Add)
10. O_2 Analyzer
11. CO_2 Analyzer
12. CO_2/O_2 Sample Line
13. Water Containment Ark
14. HP Supply Whip
15. HP Supply Gauge
16. Chamber Depth Gauge
17. EDF Chamber Complex
18. Oral Pressure Transducer (Wet Mount)
19. Loop Equalizing Solenoid
20. Expired Gas Heater Coil (Typical 3 Ply)
21. Canister Bed Thermistors
22. O_2 and CO_2 Analysis Pickup
23. Diver's Umbilical Supply
24. Volume Tank
25. Umbilical Diff. Pressure Transducer

Figure 4-11. CATEGORY 5 UBA TEST Setup

4-12.4 Test Setup

Test equipment shall be configured within the test facility similar to Figures 4.5 and 4.11 paying particular attention to the flow restrictions.

4-12.4.1 Parameters to be Controlled

1. The controlled parameters including the breathing simulator settings, are contained in Table 3.1. These parameters are restated in this section for ease of reference.

Table 3-1. BREATHING SIMULATOR SETTINGS

f (BPM)	**V_T (Liters)**	**RMV (L/min)**	**Diver Work Rate**
15	1.5	22.5	Light
20	2.0	40.0	Moderately Heavy
25	2.5	62.5	Heavy
30	2.5	75.0	Severe
30	3.0	90.0	Extreme

2. Exhalation/inhalation time ratio: 1.00/1.00 (all test).

3. Breathing wave form: sinusoidal (all test).

4. Canister duration test to be conducted to maximum operating depth using the material being evaluated at water temperatures of -1.67, 15.56 and 32.2°C (29, 60, and 90°F) or per test plan.

5. Incremental descent stops: 0 to max test depth in 10.1 msw (33 fsw) increments (air breathing resistance test only); 0 to max test depth in 10.1 msw (33 fsw) increments (HeO_2 breathing resistance tests only); 10.1, 20.2, 30.3, and 50.5 msw (33, 66, 99, and 165 fsw) (air/O_2 consumption tests only); 15.3, 30.6, 45.9, 61.3, and 91.9 msw (50, 100, 150, 200, and 300 fsw) (HeO_2 consumption tests only) or per test plan. Tests will be conducted at deeper depths if necessary.

6. Exhaled gas temperature on canister duration tests.

7. Inhaled gas temperature on canister duration tests.

NOTE: Both inhale and exhale gas temperatures are measured at the routing tee, just downstream and upstream respectively of the routing valves.

8. Depths for canister duration tests:

   a. Air: per test plan.

   b. HeO_2: per test plan.

9. CO_2 injection for Canister Duration Test:

   a. 2.0 L/min CO_2 at an RMV of 50 L/min (for water temperatures of -1.7, 4.4, 21.1 and 32.2°C (29°, 40°, 70° and 90°F) or per test plan.

   b. 1.35 L/min CO_2 at an RMV of 40 L/min and at test temperatures.

10. Diluent: Air & HeO_2 (84/16) @ 68.95 BAR (1000 psig) supply pressure or per test plan.

NOTE: 100% O_2 will be plumbed to the O_2 side of the UBA gas addition system at 68.95 BAR (1000 psig) supply pressure, or the UBA bottle will be used with a pressure monitor.

4-12.4.2 Parameters to be Measured

1. Inhalation/exhalation peak ΔP in kPa.

2. Mouth ΔP in cmH_2O referenced to suprasternal notch.

3. CO_2 level out of scrubber in % SEV (kPa) (canister duration tests only). Measured from inhalation hose.

4. O_2 level in inhalation hose during O_2 consumption tests (%).

5. Helmet pressure drop in psi.

4-12.4.3 Data to be Computed

1. Work of breathing from P-V plots (breathing resistance test only) in J/L and kPa.

4-12.4.4 Data to be Plotted

1. Inhalation pressure at each depth (breathing resistance tests only).

2. Exhalation pressure at each depth (breathing resistance tests only).

3. Pressure vs Volume at various depths depending upon the UBA's operational limits at constant RMV and supply pressure (breathing resistance tests only).

4. CO_2 out of scrubber % SEV (kPa) vs. time (canister duration tests only).

5. Po_2 in inhalation gas (%SEV, kPa) vs. time (O_2 consumption tests only).

4-12.5 Test Procedures

4-12.5.1 Test Plan for Breathing Effort Evaluation

1. Test procedures are as follows:

   a. Ensure that the test article is set to specification and is working properly.

   b. Chamber on surface.

   c. Calibrate transducers.

   d. Perform orifice calibration procedures, per 4-3.1.

   e. Open make-up gas supply valve to test UBA.

   f. Adjust breathing simulator to 22.5 L/min RMV (1.5 liter tidal volume and 15 BPM) per 4-12.4.1.1 and take data.

   g. Adjust breathing simulator for progressive RMVs per 4-12.4.1 until all tests at this depth are completed, UBA fails, or testing is halted.

   h. Stop breathing simulator.

SAFETY NOTE: **Breathing Simulator must be operating while increasing chamber depth to prevent flooding of equipment.**

2. a. Pressurize chamber from 10.1 to 60.6 msw (33 to 198 fsw) in 10.1 msw (33 fsw) increments for air

breathing test or per test plan and repeat steps 4-12.5.1.1.f through 4-12.5.1.1.h.

b. Pressurize chamber from 10.1 to 91.9 msw (33 fsw to 300 fsw) in 10.1 msw (33 fsw) increments for HeO_2 breathing test or per test plan and repeat steps 4-12.5.1.1.f through 4-12.5.1.1.h.

NOTE: Upon completing all depths and test configuration go to step 3.

3. a. Bring chamber to surface.

b. Verify calibration with the CLM orifice and on all transducers.

4-12.5.2 Canister Duration Test

4-12.5.2.1 Canister Breakthrough Time

See Section 4-11.5.2.1

4-12.5.2.2 Canister Absorption Capacity

See Section 4-11.5.2.2

4-12.5.2.3 Mouth Differential Pressure

See Section 4-11.5.2.3

4-12.6 Post Test Shakedown

The test director will verify that all data collected is to the best of his knowledge correct and deliver the compiled test data to the task leader for report and/or technical memorandum generation.

CHAPTER 5

BREATHING RESISTANCE SOFTWARE

5-1 OVERALL DESCRIPTION

In recent years, the NEDU breathing resistance software has undergone major revision. The majority of the changes provide new information regarding tests or calibration. As always, the basic data input into the software is pressure, volume, and time. From that data are calculated resistive effort or volume-averaged pressure ($\overline{P}_V$), elastance, total harmonic distortion, phase angles, peak pressures, root-mean-square pressure, and real and reactive power. Only $\overline{P}_V$, peak pressures and elastance are immediately relevant to UBA performance goals. They are therefore considered primary measurements. The other measurements are secondary in importance, but do supply information useful in determining the validity of the primary measurements.

The printout from the analysis program includes a single pressure-volume loop along with a variety of measured variables. The breathing loop represents an ensemble average of 10 consecutive breathing loops. Ensemble averaging improves the signal-to-noise ratio of the data, suppressing purely random signals and thereby resolving periodic phenomena such as regulator chatter (Fig 5.1).

The most useful information currently provided by the breathing resistance software is found along the bottom of the breathing loop analysis printouts. The most important of these is $\overline{P}_V$, formerly termed WOB; (Fig 5.1). $\overline{P}_V$ values are compared to performance goals (Table 3.3) to determine the suitability of diving equipment. The maximum inhalation (<u>PINH</u>)† and exhalation (<u>PEXH</u>) pressures are also commonly used. Since manned testing rarely provides the volume information required to compute $\overline{P}_V$, P_{RMS} is one of the few values obtained from unmanned testing that can be compared to manned results. Its measurement requires no information about flow or volume changes; only pressure and time.

Along the right side of the analysis printout are values that have less descriptive importance than the above values. <u>ELAST</u> and <u>ELASTR</u> are two different assessments of UBA elastance. SCUBA should typically have an elastance approaching zero. In closed-circuit UBA, or helmets with neckdams, elastance can be a significant contributor to the divers' workload.

Details of the measured variables are provided starting with section 5-3.

5-1.1 Data-acquisition/analysis

There are two main computer programs, BRDATACQ.EXE and BRANAL.EXE, which are run by T&E operator personnel by invoking the batch file TEST.BAT on the DOS

†Words in underlined capital letters (e.g. <u>PINH</u>) are the names of measurements displayed by the analysis program. Words in all capital letters (BRANAL) represent program names, except for commonly capitalized terms such as SCUBA and UBA. Italized words (*estim_area*) represent mathematical functions or small sections of code.

computers. TEST.BAT first executes BRDATACQ, which communicates directly with the data acquisition hardware (National Instruments AT-MIO-16 A/D board), scanning data from the breathing simulator machine and from the pressure transducer. When selected by the T&E operator, the program enters "analysis mode," wherein it begins looking for complete breathing loops in the incoming data. In analysis mode, when a breathing loop is identified it is written to a file on disk until a sample of 10 breathing loops has been acquired. Then the program computes an ensemble-average of the 10 breathing loops and switches out of analysis mode. When the operator wants to acquire breathing loops again, he must enter analysis mode again. In addition to acquiring breathing loops, the program computes some simple statistics on the breathing loop data. These statistics are also stored on disk with the breathing loop data. The 10 breathing loops are stored in a disk file with file extension BRS. The ensemble-averaged loop is stored in a disk file with file extension BRX.

After the operator is finished testing the breathing equipment, he terminates the program and the next program, BRANAL, is invoked by the batch file. BRANAL performs additional analyses on the breathing loop data that are too time-consuming to perform during data acquisition. BRANAL automatically retrieves all BRX (averaged loop) data from the latest execution of BRDATACQ, computes some additional statistics for each BRX loop, and produces screen-image files on disk for later printing.

5-1.2 Calibration program

BRETHCAL.BAT is a batch command file which calls up the BRCAL.EXE program. BRCAL performs calibration of the 486 computer for the pressure and linear motion transducers. This is a menu-driven program, allowing the operator to choose calibration for pressure, calibration for linear motion transducer (breathing machine), or both. A basic assumption is that the transducers are linear. Therefore for each transducer two parameters determine the conversion from raw signal (voltage) to engineering units: slope and intercept (C1 and C0). BRCAL computes these parameters for each transducer and writes the values of C1 and C0 into the appropriate record in a transducer database file, XDUCER.DBF (note that XDUCER.DBF is in dBase format). The parameters stored in XDUCER.DBF are used by the Breathing Resistance acquisition program to convert input voltages from the transducers into engineering units.

5-1.3 Archival database program

There exists a database (called BRXALL) on the LAN, which contains historical data on all T&E work-of-breathing experiments since Dec 5, 1990. The database is indexed by the name of the BRX (or BRS, in the case of the older data) file that resulted from the experiment. A program called BRXDB updates this database from the most recent BRX data. BRXDB is called up by the ARCIT archival program.

5-1.4 Data archiving program

The program ARCIT prints graphic output from BRANAL, compresses all data produced by BRDATACQ and BRANAL, copies the compressed data to the LAN file server, and deletes the data from the local computer's hard disk drive.

5-1.5 Orifice cal WOB trend program

The program CALTREND scans the database BRXALL looking for orifice cal records. From this data, it produces screen plots of WOB trends for each standard RMV level. A user-operated graph-cursor allows the user to display the date and time associated with any point on the trend plot. This program is intended for quality-control purposes. It allows the user to see graphically any significant departures from normal WOB values.

5-1.6 Regulator statistics program

The program REGSTAT scans the database BRXALL looking for regulator records. From this data, it produces a screen plot of WOB trend for the depth and RMV selected by the operator, and computes the mean and standard deviation for the WOB in this group of regulator records.

5-2 BRX DATABASE

A program has been created which retrieves information about past T&E experiments and relate this information to the BRX files. The program BRXDB scans all the files in the current working directory, extracts the heading data from the first few records of each file, and inserts this data (along with the name of the BRX file) into a database file called BRXALL.DBF. This database file is indexed on the BRX name. The master database resides in f:\adp\t&e\brx. In f:\public\bats, there is a batch file called SEEBRX that, when invoked, copies the BRXALL database and its corresponding index from adp\t&e\brx and executes the Saber Browse utility. The T&E archiving procedure (ARCIT) runs BRXDB to update BRXALL in adp\t&e\brx from the current BRX files. Note that in the process of updating the database, the BRXDB program checks the BRXALL index in order to prevent duplicate BRX names from appearing on the database.

5-3 WORK OF BREATHING

Resistive work of breathing (W) is defined as the area enclosed by the breathing loop. It is expressed in Joules (note that one kPa liter = one Joule). However, since different tidal volumes will result in different values for W, for the purposes of comparing breathing rigs (possibly tested with different tidal volumes) we are really interested in a normalized W which is computed by dividing the area of the breathing loop by the tidal volume. This value thus has units of joules per liter or kPa. It is properly referred to as volume-averaged pressure (P_V) or Resistive Effort. In the recent past, this average pressure was termed, erroneously, Work of Breathing (WOB).

W is computed by a device frequently used to find areas of figures in elementary calculus courses: if the figure is bounded by an upper curve and a lower curve, then the area under the upper curve is computed. Then the area under the lower curve is computed. The difference in these two areas is the area enclosed by the two bounding curves. In this method, the upper curve is the exhalation portion of the breathing loop, and the lower curve is the inhalation portion of the loop. In order to ensure that the "area under the curve" is positive, we must shift the breathing loop upward till all of its points are on or above the horizontal axis.

In the loop-acquisition program, W is calculated as follows. The function *analyze_cc_loop* calculates the peak inhalation pressure PINH (normally a negative number). Each value in the array of inhalation pressures is then transformed by the amount pinh. This will result in a vertical translation of the inhalation curve upward so that the lowermost point on this curve just touches the volume axis. The area under the inhalation curve is computed by a call to the function *estim_area*. The area-estimation algorithm in *estim_area* estimates the area under the inhalation curve by taking adjacent pressure coordinates as two vertices of a trapezoid and taking the corresponding adjacent points on the horizontal axis as the other two vertices. The area of this trapezoid is computed for each pair of adjacent points in the input array, and the areas are summed to produce the area under the curve. The function *analyze_cc_loop* then translates the exhalation curve upward by the amount of PINH and repeats the steps to estimate the area under the exhalation curve, and then subtracts the area under the inhalation curve from the area under the exhalation curve to give the total W. After *analyze_cc_loop* establishes the total W via the area calculation, the function *analyze* computes $\overline{P}_V$ by dividing by tidal volume.

5-4 PHASE CALCULATION

PHASE is the phase angle between pressure and flow. It provides information about the type of impedance into which the diver is breathing[17]. Phase angles (in degrees) are used in the estimation of real and reactive power. Power measurements combine characteristics of the UBA impedance and the respiratory minute ventilation. They are experimental values whose usefulness has yet to be proven.

The function *phasedif* computes the phase difference between the pressure and flow wave forms. The first step in this calculation is the computation of the flow, which is the time derivative of the volume. The discrete derivative of the volume signal at a given time is the difference in adjacent volume values divided by the corresponding difference in time. In computing the flow array from the volume array, the convention is that the exhalation flow is positive and the inhalation flow is negative (in a purely resistive system, e.g. orifice cals, the pressure should be in phase with the flow). Note that the flow is computed in the main program, *loopdata*. The phase difference between the pressure and the flow is then computed by calling the function phasedif.

To find the phase difference between the pressure and the flow, the flow array is shifted by one position and the total cross-correlation between the pressure and flow arrays is computed. Note that this is a circular shift, so that the element shifted off the end of the array is put back onto the front of the array. The total cross-correlation between two arrays x and y is defined to be the sum (over all i) of all products of the form $x_i \cdot y_i$. The flow array is then circularly shifted again and the total cross-correlation is computed again. This process continues for all possible shifts, i.e. until the flow array has been shifted all the way back to its original position. During this process the cross-correlation values are stored in another array in which the subscript of that array indicates the corresponding shift amount. For example the 50th element of the cross-correlation array contains the cross-correlation between the pressure and flow when the flow has been shifted by 50 elements.

After all shifting and computing of cross-correlations has been done, the subscript (i.e. shift) corresponding to the maximum cross-correlation is saved. This indicates the amount of

shift necessary to put the pressure and flow in phase with each other. If the flow array is of length *npts*, then shifting this array by *npts* elements corresponds to a shift of the array by 360 degrees. Dividing the shift amount by *npts* and then multiplying by 360 degrees gives the amount of shift in degrees.

5-5 ENSEMBLE-AVERAGING

The purpose of the ensemble-averaging algorithm is to smooth out noise in the pressure and volume signals by performing a pointwise average of the breathing loops in the "ensemble" of 10 loops, producing an averaged loop. However, a strictly pointwise average is not possible, due to the fuzzy nature of the loop recognition process (function *find_loop*). Since the beginning and end of a breathing loop are not exactly determined but are only approximate, the breathing loops in an ensemble may not contain the same number of data points. Hence it is impossible to exactly match a given point in one loop with corresponding points in the other loops.

This difficulty has been handled by expanding the concept of a "point" to be a small but finite interval on the volume axis, as recently described by Altman[18]. Any volume/pressure points, in any of the 10 loops, whose volume coordinates happen to fall within this small interval will be considered to be the same "point" for the purpose of this calculation, so that their volume coordinates and pressure coordinates will be averaged to produce a single volume/pressure point. In statistical literature on kernel nonparametric regression, this small interval on the volume axis is referred to as a "window." The crucial question in this technique is to decide how wide the window should be.

The question of how to choose the window width is closely related to the question of how many data points should be produced in the averaged loop, since the number of output data points is the same as the number of windows. The number of windows times the window width should give us the tidal volume. Suppose we assume that the number of data points in the averaged loop should be the <u>average</u> of the numbers of points in each of the 10 individual loops. This assumption then determines the window width as follows: take the tidal volume and divide it by the average number of data points (which will be the number of points in the averaged loop). The result is the window size. Actually there will be two window sizes: one for the inhalation side of the loop (in which volume measurements go from zero to the tidal volume), and one for the exhalation side of the loop (in which volume measurements go from the tidal volume down to zero).

The function *loop_avg* first computes the ensemble-average of the inhalation data. First the left-hand limit (called *xcoord* in the program) for the first window is set to 0 liters (the right-hand limit is *xcoord+inwin_size*). The accumulators for volume and pressure, and the point count, are cleared to zero. For each breathing loop in the ensemble of 10 loops, we scan the volume data looking for volume points that fall within the window. When such a point is found, it is counted and its pressure and volume values accumulated for the average. To aid in this process of scanning the data falling within a window, some additional data items are used: a flag which is turned off when the data scan has gone past the end of the current window (indicating that we need to go to the next breathing loop), and an array of 10 cursors, one for each loop. The cursors are used to save the subscripts for the beginning of the next window, so that the program can "remember" where it left off in the scan of each breathing loop.

After scanning for all of the data points (within a certain window) in all 10 loops, the average pressure value and average volume value are calculated. The window is then shifted to the right by one inhalation-window width, and the process is repeated for the next window, producing the next averaged volume/pressure point, etc. If no data points were detected within a particular window, then the program uses the last averaged volume/pressure point as the current volume/pressure point (unless we are at the beginning of the data, in which case the averaged values are simply set to 0).

The process of creating the averaged exhalation data is similar, except that the scan of the volume data takes place in reverse order, from the tidal volume down to zero.

5-6 REAL AND REACTIVE POWER

The first step in these calculations is to compute the Root-Mean-Square (RMS) power. Note that pressure times flow gives power: if the pressure is in kPa and the flow is in liters/sec, then their product will be in (kPa liters)/sec = J/sec = Watts. The RMS power is the RMS value of pressure·flow. The RMS power is then used to calculate the real and imaginary components of the power (a complex quantity). The real component of the power is the RMS power times the cosine of the angle (phase difference) between the pressure and flow phasors. The imaginary, i.e. reactive, component is the RMS power times the sine of the angle between the pressure and flow phasors.

5-7 HARMONIC DISTORTION

Harmonic distortion is a measure of the purity of a waveform. This statistic is actually a ratio that compares the system response at harmonic frequencies (i.e., frequencies greater than the fundamental) to the total system response. The breathing resistance analysis program computes the harmonic distortion of the pressure signal. Harmonic distortion serves two purposes. In an open-circuit system it quantifies the degree of regulator chattering (Figure 5-1), and in a closed-circuit UBA it provides information regarding the linearity of the elastance curve.

The total harmonic distortion (THD) is computed from the power spectrum of the pressure signal. The first step in the calculations is the expansion of the pressure data array to be a power of 2 in length. This is required by the *Spectrum* function which uses the Fast Fourier Transform (FFT) algorithm to compute the power spectrum. (Note that the FFT algorithm requires its input to be a power of 2 in length). This expansion is accomplished by simply repeating the pressure data until it fills up an array of 1024 elements.

Next a Hamming window is applied to the pressure data to suppress spectral leakage, and the function Spectrum is called to generate the power spectrum of the pressure signal. Since we are only interested in positive frequencies (a so-called single-sideband FFT) we double the power magnitudes that were returned by the *Spectrum* function.

The power data returned by *Spectrum* corresponds to frequencies 0, 1, 2, 3, etc. For the

compute the harmonic distortion, we must identify the fundamental frequency. This is done by searching the array of power spectrum values to find the largest value. This search deliberately skips the zeroth frequency, which corresponds to the steady-state component of the signal. Once the fundamental has been identified, we define a cutoff frequency to be 1.5 times the fundamental. The power contained in the spectrum above this cutoff frequency is accumulated. The power contained in the entire spectrum (except the zeroth frequency) is also accumulated. The harmonic distortion is the ratio of these two quantities.

Figure 5-1 shows the effect of increasing RMV on a chattering SCUBA regulator. Each loop is an ensemble average of 10 breathing loops. As RMV increases, the chatter increases, as evidenced by an increasing THD.

Further discussion of these topics can be found in "Fast Fourier Transforms and Power Spectra in LabWindows," National Instruments Application Note 020.

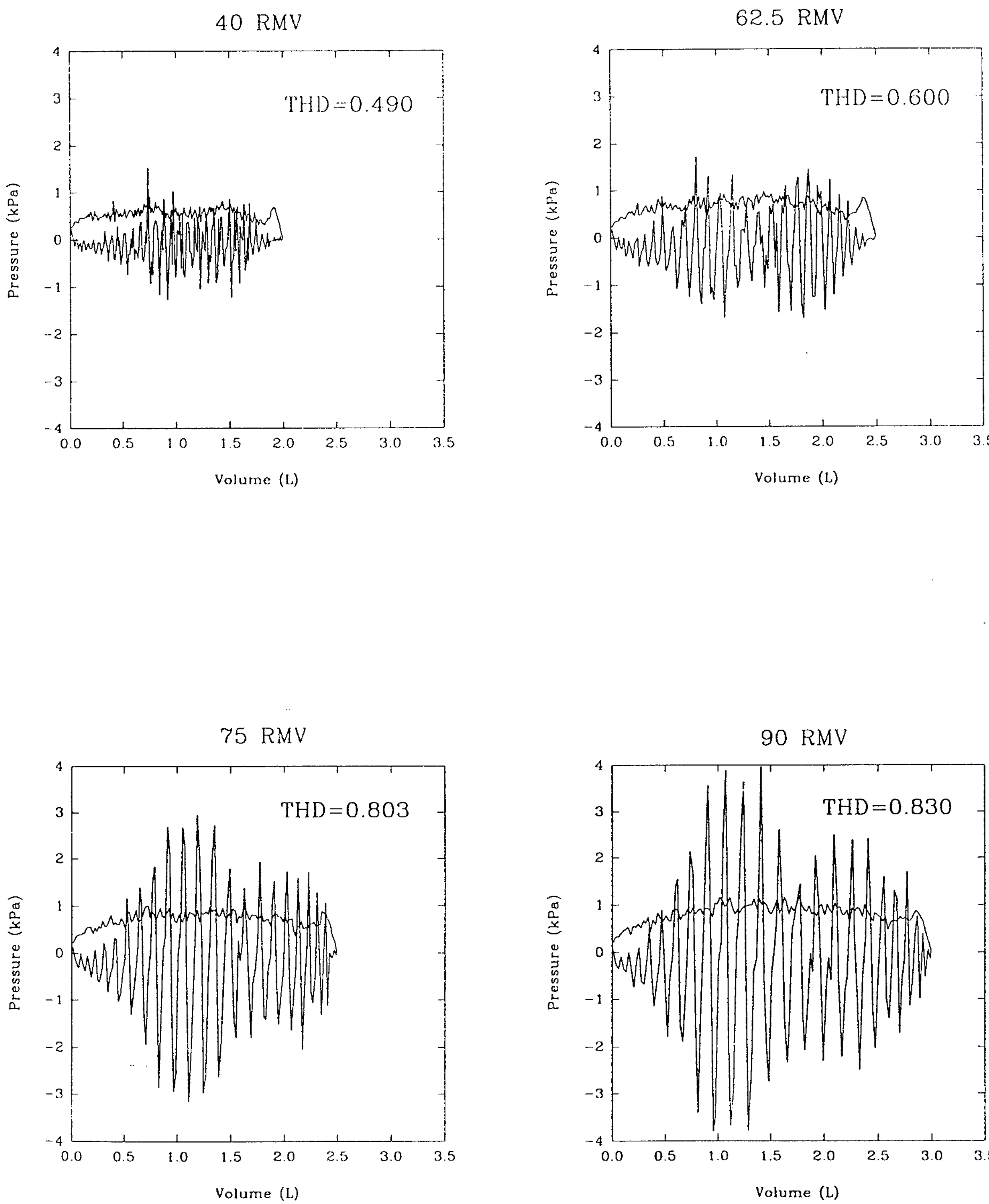


Figure 5-1. Total Harmonic Distortion (THD) and Regulator Chatter

5-8 ARCHIVING

After running a series of tests, the breathing resistance data archiving program, ARCIT should be run. This program performs the following functions:

1. Compresses the BRX, BRS, and PRT files and copies these compressed files to LAN directories adp\t&e\brx, adp\t&e\brs, and adp\t&e\prt, respectively.

2. Directs the PRT files to the T&E Laserjet printer.

3. Updates the BRXALL database on the LAN with the appropriate information from the BRX files.

4. Deletes the BRX, BRS, and PRT files from the local hard disk.

Note that ARCIT does not delete the compressed files from the local hard disk. Periodically ADP personnel should check the hard disks in T&E for ZIP files, verify that those ZIP files are actually backed-up properly to the LAN, and then delete those ZIP files from the hard disk.

ADP personnel should periodically monitor disk space usage (on the LAN file server) by this archived data. If the space taken up on the file server becomes excessive, the older data should be off-loaded onto CAROM cartridge. The CAROM which we use to store the Breathing Resistance archival data is in the NEDU Tech Library. Check the CAROM cartridge out from the librarian, off-load the necessary data onto the cartridge, and then return it to the librarian.

ARCIT can be executed in either of two ways: with or without entering a command-line date. If ARCIT is run without entering a date on the command line, the program uses the current system date in the names of the output archival files it creates. If you wish to use a different date than the current system date (e.g. if you want to archive data collected on the previous day), execute ARCIT with a command-line date in the format YYMMMDD. For example: ARCIT 93JUL13. ARCIT checks entered dates for correctness of format.

5-9 BPM AND TIDAL VOLUME ADJUSTMENTS

The transducer database, XDUCER.DBF, actually has two uses. It contains transducer coefficients for the conversion of raw voltage signals into engineering units, and it contains standard values for all the BPM and tidal volume levels that will be used on that data acquisition system. These standard values from XDUCER.DBF are used by the calibration program to determine at what tidal volumes and corresponding BPM values the system should be calibrated. These data are also used by the PVSCAN and PLOTLOOP modules, which need to know what are the acceptable standard values of BPM and tidal volume.

To change the tables of standard BPM and/or tidal volumes, use dBase to edit the XDUCER.DBF file. There must be one record for every valid tidal volume/BPM combination.

Another file, RMV.DBF, contains a list of each standard RMV value, along with its associated max and min acceptable WOB values for orifice cals. If the standard RMV levels are modified, i.e. an RMV value is added or deleted, then this file must be edited with dBase to make the appropriate changes.

5-10 BATTELLE BREATHING SIMULATOR

The Battelle breathing simulator contains an embedded computer that drives a Galil motor controller. The embedded computer is programmed to accept user commands and control the Galil motor controller in accordance with these commands. The commands used by T&E's Battelle are as follows:

VOLUME=X.X where X.X is the desired tidal volume in liters. Example: VOLUME=2.0. This command sets the value of the VOLUME variable in the program (called BREATH) in the embedded computer.

RATE=XX where XX is the desired breathing rate in breaths per minute. Example: RATE=30. This command sets the value of the RATE variable in program BREATH.

XQ#BREATH executes the program BREATH in the embedded computer inside the Battelle. This has the effect of starting the breathing simulator.

ENABLE=0 terminates the program BREATH in the embedded computer inside the Battelle. This has the effect of stopping the breathing simulator.

Each command must be terminated by a carriage-return character ('\r' in C).

The module SETRMV.C handles the interface between the operator and the Battelle breathing machine. It builds selection lists of standard values of Tidal Volume and BPM, from the tables created in the function est_pv_scan (note that to modify the contents of these selection lists, you should use dBase to modify the XDUCER.DBF and XDUCER.NDX files, where the standard values of Tidal Volume and BPM are stored). SETRMV processes inputs from the GUI, translates them into breathing machine commands, and sends the commands to the Battelle through COM port #1.

SETRMV is used by both the loop-acquisition program BRDATACQ and the calibration program BRCAL. In each of these programs, the capability to control the Battelle breathing machine is optional, because some of the systems in T&E use Battelle breathing machines, and some use Reimers (a non-computerized breathing simulator which must be operated with manual controls). To execute BRDATACQ and use the Battelle, enter a command-line argument after the command "BRDATACQ". It does not matter what the argument is, since the program uses the command-line argument count to determine whether the Battelle option is to be enabled.

Executing BRDATACQ without a command-line argument tells the program that the Battelle is not being used. Consequently the program will hide the screen control that activates the Battelle GUI screen, so the operator will not even see it. The calibration program BRCAL (executed by batch file BRETHCAL.BAT) has exactly the same Battelle option. The batch files

TEST.BAT and BRETHCAL.BAT are customized for each system so that the Battelle option will either be set or not, as appropriate for that system.

If a system is using a Reimers breathing machine and you want to convert it to use a Battelle instead, you must

1. Modify the TEST.BAT file to put a command-line argument after the word BRDATACQ.

2. Modify the BRETHCAL.BAT file to put a command-line argument after the word BRCAL.

3. Plug in the RS232 cable from the Battelle breathing simulator into the COM port #1 in the back of the PC.

CHAPTER 6

THE TESTING OF ELECTRONIC UBA

6-1 INTRODUCTION

Electronically controlled, closed-circuit UBA pose a unique set of requirements for the test and evaluation laboratory. They are sophisticated devices with both hardware and software systems that require testing. Examples of these systems are:

O_2 sensors
O_2 control algorithms
alarm algorithms
alarm circuitry
CO_2 canisters
O_2 and diluent-add valves
breathing circuits

Unmanned testing of the above subsystems should, at the very least, provide some confidence that the UBA is safe for manned testing. When used optimally, unmanned testing can provide UBA reliability data that would be realistically impossible to obtain otherwise.

6-2 RELIABILITY

Historically, NEDU has estimated parameters of UBA operation such as canister duration or work of breathing. However, it is now apparent that we must estimate UBA reliability before committing divers to test unproven, electronically controlled diving rigs. Unfortunately, the only way to be confident that a UBA is reliable is to conduct a large number of tests.

6-2.1 Number of Tests

There is a positive correlation between the number of tests run on a UBA and the certainty of the testing conclusions. However, the numbers of required tests are also dependent on the type of information being sought. If only the average CO_2 canister duration for a particular environmental condition is desired, five to ten tests should be adequate. Of course, since each test could last more than 15 hours, even five tests would be a considerable testing effort. On the other hand, if proof is wanted that the reliability of the O_2 control circuitry on a closed-circuit UBA is 0.999, with only one failure in 1000 dives, then thousands of tests may be necessary.

6-2.2 Reliability Estimates

Generally, reliability estimates are based upon the statistical properties of binary (pass/fail) tests. *(The probabilities associated with those tests are described by the binomial distribution.)* NEDU uses these estimates to predict the likelihood of a critical UBA failure. A critical failure is a complete, catastrophic system breakdown, resulting in loss of O_2 control and loss of alarms. Such a failure would put the life of an affected diver in serious jeopardy. For this reason, each

dive with a UBA is considered to have one of two (binary) outcomes; either good or bad. Either the rig functioned or it suffered a critical failure.

Reliability estimates in turn have two components. One component is the estimate of reliability itself, and the other is a measure of confidence in that estimate. The manner in which the numbers of tests and confidence levels interact to yield reliability estimates[19] is shown in Table 6-1. To use Table 6-1, one must decide ahead of time what reliability and confidence level is needed for a particular UBA or UBA subsystem. The numbers found at the intersection of the columns (confidence level) and rows (minimum reliability) are the number of tests that must be conducted **without a failure** to support the desired reliability level (failure rate = 1 - reliability).

Table 6-1 Sample Size with No Failures For Minimum Reliability Levels

	Confidence Level			
min Reliability	.90	.95	.98	.99
.998	1151	1497	1954	2301
.995	460	598	781	919
.99	230	299	390	459
.95	45	59	77	90
.90	22	29	38	44

If 29 tests of a UBA were performed with no critical failures, then the estimated UBA reliability would be at least 0.90, with 95% confidence. This somewhat arcane statement means that if the true (and unknowable) reliability were as low as 0.90 with a failure rate of 0.10, then our test result (0 failures in 29 tests) would be seen up to 5% of the time. It also means that it is unlikely (less than 5% chance) that the true failure rate would be greater than 0.10.

We therefore conclude that given perfect test results (no bad outcomes out of 29 tests), the true UBA reliability could nevertheless be as low as 0.90. That is, there could be as much as a 10% critical failure rate. If by chance a critical failure did occur during the 29 tests, there would be at least a 5% chance that the failure rate was **higher** than 0.10. **In that case, the UBA would be immediately disqualified from further testing.**

6-2.3 Graded Reliability Testing

The safest and most efficient way to test a new UBA is through graded reliability testing. Graded testing is designed to expose an experimental diver to the lowest possible risk compatible with accomplishing the testing mission.

Potential risk is based on the diving condition. It is an estimate of the probable outcome for a diver if a critical failure of the breathing apparatus occurred. For example, an open ocean dive at 300 fsw without diver monitoring or emergency backups would be a high potential risk situation. A test on an instrumented diver at 15 fsw in a pool with stand-by divers and a treatment chamber would be a low potential risk condition. The estimate of potential risk is subjective - it can not be accurately defined.

The *expected risk* is a product of the potential risk and the UBA's *failure rate* (1-reliability). (Fortunately, failure rate can be quantified.) If a UBA's reliability is high, failure rates are low. Therefore, even if a diver is placed in a potentially risky dive situation, the expected risk can be low.

$$Risk_{expected} = Risk_{potential} \cdot (1 - reliability)$$

Graded reliability testing should maintain a low expected risk while continuously increasing the confidence in the UBA's reliability. In other words, the greater the potential risk to a diver, the greater must be NEDU's confidence in the UBA before the diver is exposed to that risk.

The following is an example of how graded reliability testing can be implemented. The testing is distinguished by several levels, which are in turn characterized by three questions:

Level 1: Is a rig safe for manned, monitored, pool testing?

Strategy: At the beginning of UBA testing, reliability is not established. Therefore, expected risk is made low by eliminating divers from the test and conducting only unmanned tests.

If 15 unmanned tests are conducted without a failure, then a reliability estimate of 0.90 can be made with 80% confidence (Table 2). This is the same reliability criterion used by OPTEVFOR (Operational Test and Evaluation Force) for the successful passing of UBA Technical Evaluation. If this degree of reliability is obtained, it is reasonably safe to progress to the next level of testing.

Level 2: Is the rig safe for manned, monitored, OSF testing to the maximum planned operating depth?

Strategy: Conduct manned pool tests. If 14 pool tests are conducted with no failures then the combined 29 trials (unmanned + pool tests) yields a minimum reliability estimate of 0.90 with 95% confidence limits (Tables 1 and 2).

Level *3: Is the rig safe for manned, unmonitored, open ocean technical evaluation?*

Strategy: Perform at least 30 tests in the NEDU Ocean Simulation Facility and combine the results from unmanned, pool, and OSF tests. With a total of 59 tests with no critical failures, estimated minimum reliability would be 0.95 with 95% confidence (Tables 1 and 2). If unmanned tests are excluded from the dataset (leaving a sample size of 44), reliability would be

estimated at a minimum of 0.93 with 95% confidence.

Table 6-2 Graded Reliability Testing

Level	Reliability	conf. lim.	# runs	total runs
1	90%	80%	15	15
2	90%	95%	14	29
3	95%	95%	30	59

Each level of testing exposes the diver to greater potential risks. Yet at the same time, estimates of reliability will have increased at each level, as long as no critical failures occur. Therefore, expected risk remains low throughout the testing sequence.

6-3 SOFTWARE TESTING

Modern UBA are making increased use of on-board computers and software to control various functions. NEDU tests those functions on the laboratory bench with the aid of testing computers. However, the software testing conducted at NEDU is a minimal test program. It is no substitute for the exhaustive software testing that should be conducted by the developer.

6-3.1 O_2 Control Algorithms

PO_2 in the UBA breathing loop is typically sensed by 3 redundant sensors. A controller (on-board computer) monitors the 3 sensor readings and performs various actions depending upon a set of logical rules (collectively known as an O_2 control algorithm). These rules attempt to control PO_2 within narrow limits in spite of changing dive conditions and potential sensor failures.

The effectiveness of the control algorithm can be tested through a computer simulation. The actual UBA is not required. The random failure of O_2 sensors can be simulated, and the algorithm's ability to control O_2 monitored. The O_2 control algorithm can be reproduced in the testing computer's software (Appendix A6). In this manner, thousands of sensor failures can be simulated.

The sensor failure modes that should be tested are:
1) Complete failure of the sensor (0 voltage output)
2) Sensor "lock-out" where the sensor quits responding
3) A combination of total failure and lock-out.

A lock-out is a failure mode where the sensor is shielded from ambient O_2 by a barrier, usually water. The sensor initially reports the O_2 reading present at the moment of lock-out. That reading will slowly decline independent of changes in UBA O_2. That decline is due to consumption of trapped O_2 by the sensing electrode.

The result of failing 1 to 3 sensors at a time should be tested. When the algorithm loses

control of the PO_2, the testing computer should note whether the failure results in the continued opening or closing of the O_2-add valve. This would determine whether a diver would be likely to suffer a hypoxic or hyperoxic event.

The aim of these tests is to demonstrate that the algorithm accomplishes the following:
1) The risk of loosing control of the rig before failure of all three sensors should be minimal.
2) The preferred failure mode would be hyperoxia.

If total sensor failure occurs shallow, hyperoxia is survivable, hypoxia may not be. Secondly, O_2 seizures are less likely to result in cardiac arrest than hypoxia. This **might** give the diver some advantage if immediately rescued.

6-3.2 Alarm Logic

If the UBA controller detects a sensor failure or observes a loss of O_2 control, then the diver should be warned by an alarm. The diver can then operate the UBA manually while aborting the dive. Obviously, if the alarm fails to operate correctly, the diver will be in jeopardy. Consequently, the reliability of this alarm system has to be extremely high (>0.999). Unfortunately, to assure this level of reliability, thousands of tests of the alarm circuitry have to be conducted. This degree of testing of the UBA controller, alarm logic, and alarm circuitry can only be conducted with the aid of computers. Fortunately, this testing can be accomplished on a bench top.

Three stable millivolt sources are assembled with tuning capability across the range of nominal sensor voltage. These sensor simulators applied voltage to three computer controlled relays. Testing begins with all relays closed and sensor voltage levels equal to the desired PO_2 set point. This places the apparatus in a stable "no control required" status.

When the testing software issues a command to open one or more of the relays, the voltage of the affected sensor drops to essentially zero, and initiates the sensor failure sequence within the UBA software. Lag time between failure and alarm is tracked by both systems. The duration of the failure pulse exceeds the alarm lag time by 5 seconds to insure a positive count of each alarm.

When alarms are triggered, a voltage is generated that can be monitored by the analog to digital (A/D) capability of the testing computer. If both audio and visual alarms are possible, both must be monitored.

If the alarm logic is replicated within the testing computer, then the number of alarms that **should** have been generated can be compared against the number of alarms that **were** generated. The differences between the theoretical and the actual number of alarms is an index of the logic and circuit reliability. For a reliability estimate of 0.998 with 99% confidence, 2301 alarm conditions would have to be generated without a single alarm malfunction (Table 6-1).

Discrepancies between theoretical and actual alarm counts are possible due to multiple, transient sensor failures occurring within a short interval (that interval being a designed "alarm reset" period), or due to idiosyncracies of the Macintosh programming (Appendix B). Those

discrepancies would not indicate a fault of the UBA. For that reason, a continuous log of the testing activity has to be recorded by the computer, with each discrepancy checked manually to determine its origin.

6-4 HARDWARE TESTING

6-4.1 Real Life Simulation

Closed and Semi-Closed Circuit UBA should be tested in as realistic a scenario as possible. That is, O_2 consumption and CO_2 production should be simulated simultaneously. Although technically challenging, only this test will check operation of the O_2 control system under the conditions of heat and high humidity generated by the CO_2 scrubber. This test requires that a budget of gas removal and CO_2 and inert gas injection be prepared for each test depth. An example budget is shown below. The simulated O_2 consumption procedure is described in Section 4-11.5.4.

The following example balance sheet is for a high workload, nitrox dive at 15 fsw. $\dot{V}CO_2 = 1.6\ L\cdot min^{-1}$. With an assumed gas exchange ratio of 0.9, $\dot{V}O_2 = 1.78\ L\cdot min^{-1}$. All volumes are expressed as STPD, Standard Temperature (0°C), Pressure (760 mmHg) and Dry.

<u>Volume Balance per Minute</u>

-2.37 liters	gas withdrawn (0.75 ATA O_2 in air)
+0.59 liters	100% N_2
+1.60 liters	100% CO_2
-1.60 liters	CO_2 absorbed by canister
<u>+1.78 liters</u>	100% O_2 injected by UBA
0 liters	net change of UBA volume

Conversions from STPD to ambient conditions are required to find the flow rates for flow meters at 1 ATA. The software for making those conversions is called STPDATPS.exe and is available on any DOS style computer in the T&E laboratory.

To test the ability of a UBA to respond to changing conditions, a variety of work profiles should be used. For example, the balance sheet above would be for a moderately stressful baseline work profile (40 $L\cdot min^{-1}$ RMV, $\dot{V}O_2 = 1.76\ L\cdot min^{-1}$, $\dot{V}CO_2 = 1.6\ L\cdot min^{-1}$). On the half hour a low work scenario could be tested for 5 minutes (22.5 $L\cdot min^{-1}$ RMV, $\dot{V}O_2 = 1\ L\cdot min^{-1}$, $\dot{V}CO_2 = 0.9\ L\cdot min^{-1}$. On the hour, a high work scenario could be tested for 5 minutes (75 $L\cdot min^{-1}$ RMV, $\dot{V}O_2 = 2.22\ L\cdot min^{-1}$, $\dot{V}CO_2 = 2\ L\cdot min^{-1}$).

Flow meters used for gas transfer to and from the rig will be calibrated using a volume standard (Tissot gasometer) on the day of the test.

6-4.2 UBA Attitude

Motion of a UBA can precipitate failures, especially if there exists an appreciable volume of condensed or leaking water within the UBA. Therefore, an effort should be made to change the orientation of the rig during testing.

Accordingly, closed and semi-closed circuit UBA are to be tested immersed in several attitudes including vertical, head up; prone - horizontal with the manikin's face down, and with various degrees of tilt. An entire test does not need to be conducted in each position. However, means must be available for varying attitude during the tests. The Weaver Wobbler is a pneumatically controlled, buoyancy driven platform that allows an attached UBA to undergo limited changes in attitude in the pitch and roll axes during testing.

CHAPTER 7

STATISTICALLY BASED DECISION MAKING

7-1 INTRODUCTION

The end result of any test of diving equipment or operating procedure is a recommendation to NAVSEA. This chapter describes procedures for analyzing test data so that NEDU's recommendations convey a fair and accurate impression of the equipment or procedure based on valid scientific methods.

The analytical methods described below are meant to be demonstrative, not all-inclusive. The methods are available in most but not all statistical software packages. Two of the more useful and user-friendly software packages available at NEDU are StatGraphics (STSC, Inc.) and SigmaStat (Jandel Scientific).

The following sections are formatted in the form of commonly asked questions, along with proposed solutions. The examples given below serve only as a guide for the uninitiated. Specialized training would be required before the majority of these procedures could be successfully implemented.

To ease the transition from old to new terminology, we will retain the old terminology of WOB in this chapter. In future revisions of this manual, however, only the correct terminology will be used. The correct symbols are W for work, and $\overline{P}_V$ for resistive effort, replacing WOB.

7-2 QUESTIONS AND ANSWERS

7-2.1 Does a regulator meet NEDU performance goals?

The statistical methods described below are standard quality control procedures. They apply whenever one wishes to determine whether a product meets legislated requirements such as air pollution standards. Examples can be found in beginning level textbooks of modern business statistics; for example, McClave and Benson[20].

Solution:

1. Test more than one regulator (typically 5 examples of a particular model are required for any degree of statistical certainty).

2. Tabulate the WOB ($\overline{P}_V$) for each regulator for each combination of depth, temperature, and RMV tested.

3. Determine the sample mean and standard deviation (SD) for each condition.

4. If the mean is greater than 1.37 kPa, and the SD is greater than 0.2 kPa, the regulator is disqualified. If SD is less than 0.2 kPa, proceed.

5. Perform a one-sided, one-sample T-test comparing the hypothesis that the mean WOB is less than or equal to the NEDU performance goal, versus the alternative that the mean WOB is **greater** than the goal. This test is available in StatGraphics. *(For SCUBA regulators, the goal is 1.37 J/L up to an RMV of 62.5 L·min^{-1} for any depth down to 132 fsw on air.)*

4. If the probability (P) for the test is less than 0.05, the WOB for the regulator significantly exceeds the NEDU performance goal. Otherwise, it is acceptable.

Example I

The individual WOB for five regulators were as follows: 1.22, 1.39, 1.42, 1.47, and 1.29 kPa. The mean and standard deviation (SD) was 1.36 ± .10 kPa. Since an SD of 0.1 kPa is less than 0.2 kPa, the batch of regulators is reasonably consistent and therefore qualified for further analysis (see section 3-10.2.1.2). The P (probability) value for the one-sided, one-sample t-test was 0.60 (<0.05 needed for significance). Therefore, the WOB for these regulators was not significantly greater than the goal of 1.37 kPa (J/L).

Example II

The WOB for five regulators was 1.38, 1.38, 1.90, 1.53, and 1.56 kPa. The mean and standard deviation was 1.55 ± .21 kPa. The mean was above 1.37 kPa and the standard deviation exceeds 0.2 kPa, so no further analysis should be performed. The variability from regulator to regulator is too great to consider Navy use of this regulator.

When regulator WOB is highly variable, it may be impossible to prove that the regulators do not meet the performance goal unless the standard deviation were itself a qualifying characteristic. As an example, for this data the one sided, one-sample t-test showed that the mean of the sample **was not statistically greater** than the goal of 1.37. In other words, if the manufacturer's quality control is bad enough, statistical tests become worthless. Statistical comparison with the goals should only be run on data that qualifies for complete analysis by having a standard deviation less than 0.2 kPa.

In NEDU Report 3-81, the goal of 1.37 J/L (kPa) was associated with ± 10% tolerance limits. In effect, that allowed any WOB up to 1.51 J/L to be accepted. By that standard, 2 of the 5 regulators approximated the target of 1.37, 2 were just above the upper tolerance limit, and 1 lay clearly above the upper tolerance limit. Logically, it would seem reasonable to condemn these regulators. By using the above statistical approach we came to the same conclusion, but more objectively.

Example III

The measured WOB for five regulators was 1.38, 1.48, 1.55, 1.65, and 1.72 kPa. The mean and standard deviation was 1.56 ± .13 kPa. The P value for the one-sided, one-sample t-test was 0.02 (<0.05 needed for significance). Therefore, the WOB for these regulators **was** significantly higher than the goal of 1.37 kPa.

7-2.2 Do two makes of regulators differ in their WOB?

Solution:

If at least five regulators of each type have been tested, a two-sample T-test can be used to examine differences between the makes under a particular condition (depth and RMV). This test is available with either SigmaStat or Statgraphics.

Example I

The individual WOBs for five regulators of Make A were as follows: 1.25, 1.29, 1.32, 1.45, and 1.58 kPa. The mean and standard deviation was 1.38 $\pm$ .14 kPa. The WOBs for five regulators of Make B were 1.38, 1.48, 1.55, 1.65, and 1.72 kPa. Their mean and standard deviation was 1.56 $\pm$ .13 kPa. The 95% confidence limits for the **difference** between the WOB of Make A and Make B was -0.38 to 0.02 kPa. A difference of 0.0 lies within the boundary of these confidence limits. The P value for the two-sample T-test was 0.07 ($<$0.05 needed for significance). Therefore, the WOBs for these regulators **were not** significantly different.

Example II

The WOBs for five regulators of Make C were 1.25, 1.29, 1.32, 1.39, and 1.45 kPa. Their mean and standard deviation was 1.34 $\pm$ .08 kPa. The WOBs for five regulators of Make B were as stated above. The 95% confidence limits for the **difference** between the WOB of Make C and Make B was -0.38 to -0.05 kPa. A difference of 0.0 does **not** lie within the boundary of these confidence limits. The P value for the two-sample T-test was 0.015 ($<$0.05 needed for significance). Therefore, the WOBs for these regulators **were** significantly different.

7-2.3 Is one regulator different from another?

This question is most pertinent when testing a single diving rig under two conditions; e.g., with and without a double exhaust valve. In this case, each rig serves as its own control.

Solution:

Five data points are obtained for each modification of the rig at each depth. Those data are the WOBs for 22.5, 40, 62.5, 75 and 90 $L{\cdot}min^{-1}$. We want to determine if the test results for the modified regulator (WOB_{mod1}) are consistently different than test results for the unmodified regulator (WOB_{mod0}).

The statistical technique of multiple regression can be used, with the dependent variable being the WOB results for regulator MOD 1 (WOBs for all five RMVs). The independent variable would be the results from the test of the unmodified rig (MOD 0).

The most useful regression is likely to be a model of the type:

$$WOB_{mod1} = B1 + B2{\cdot}WOB_{mod0}$$

where B1 and B2 are computer estimated coefficients for the model. If MOD 1 was identical to MOD 0, B1 and B2 would be 0.0 and 1.0, respectively. The purpose of this analytical test is to determine if B1 and B2 are statistically different from their expected values of 0.0 and 1.0.

If the plot of WOB against RMV is obviously curvilinear, the above model should be modified to include an additional term: $B3 \cdot (WOB_{mod0})^2$.

Example I

The WOB results for regulator MOD 0 are .25, .63, 1.44, 1.98, and 2.75 kPa for RMVs of 22.5, 40, 62.5, 75 and 90 $L \cdot min^{-1}$, respectively. We wish to determine if MOD 1 differs from MOD 0. The WOB results for MOD 1 are .27, .77, 1.78, 2.43, and 3.32 for the same RMVs. These values are called the **dependent** variables. (We want to know if these values are dependent in a predictable fashion upon the test results of Mod 0).

Multiple regression yields:

$$WOB_{mod1} = (-0.007 \pm 0.026) + (1.22 \pm 0.02) \cdot WOB_{mod0}$$

where parentheses enclose the best estimates for the model coefficients and the standard error of each coefficient. The 95% confidence limits on those coefficients are -0.090 to 0.077 for B1, and 1.17 to 1.27 for B2. The confidence limits for B2 are greater than 1.0, therefore we conclude that as WOB_{mod0} increases, the WOB_{mod1} increases faster. Statistically, therefore, the modified rig **is different** from the unmodified rig.

Example II

The WOB results for MOD 0 are .25, .77, 1.44, 2.43, and 2.75 kPa for RMVs of 22.5, 40, 62.5, 75 and 90 $L \cdot min^{-1}$, respectively. The WOB results for MOD 1 are .27, .63, 1.78, 1.98, and 3.32 for the same RMVs.

Multiple regression yields

$$WOB_{mod1} = (-0.047 \pm 0.383) + (1.08 \pm 0.21) \cdot WOB_{mod0}$$

The 95% confidence limits on those coefficients are -1.26 to 1.17 for B1 (includes 0.0), and 0.40 to 1.75 for B2 (includes 1.0). Since the confidence limits for B2 include 1.0, we conclude that as RMV increases, WOB_{mod1} increases at the same rate as WOB_{mod0}. Therefore the WOB of the modified rig is **the same as** that of the unmodified rig.

7-2.4 Comparing freeze-up and free-flow frequencies

We want to know if a regulator modification decreases the incidence of second stage freeze-ups. Suppose regulator A experienced 2 freeze-ups out of 40 trials; meaning 2 failures and 38 successes. Regulator B experienced 5 freeze-ups out of 15 trials. Is A statistically better than B?

If the number of failures for either regulator is less than 5, or the number of samples is less than 20, use the Fisher's Exact Test for a 2 x 2 contingency table. The Fisher's Exact is a so-called non-parametric test available under the category of "ratios/proportions" in SigmaStat. The resultant P for a one-tailed test is 0.013, less than 0.05. Therefore, it is safe to say that A is better than B.

If a small number of tests are run, differences are difficult to prove. If regulator C had 2 failures out of 6 trials, and D had 7 failures out of 10 trials, P would be 0.182, a non-significant value. Thus C is **not** significantly better (less prone to freeze-up) than D.

When the number of samples is greater than 40, or between 20 and 40 with failure frequencies greater than 5, then the Chi-Square Test in SigmaStat is appropriate. As a hypothetical example, fleet experience yielded the following frequencies of free-flow in MK 21 helmets: free-flow occurred on 11 out of 24 dives (frequency of 0.46) using an unmodified regulator, and on 10 out of 56 dives (frequency of 0.18) using a modified regulator. Do the free-flow frequencies for the regulators differ significantly? The Chi Square statistic is 5.424 with one degree of freedom, yielding a P of 0.02. Since this value is less than 0.05, the free-flow frequencies are significantly different.

7-2.5 How well does an accident regulator perform?

Suppose tests were run on a regulator involved in a diving incident. When tested at 99 fsw and an RMV of 40 $L{\cdot}min^{-1}$, the WOB was 2.24 kPa. How does that compare to other regulators?

Solution:

A review of previous tests of new regulators sent to NEDU for evaluation will be conducted using the database analysis program REGSTAT. Particular attention will be paid to the combination of depth and RMV believed relevant to the accident. For example, for 74 SCUBA regulators of various types tested at 99 fsw and a RMV of 40 $L{\cdot}min^{-1}$, the average WOB was 1.03 $\pm$ 0.29 kPa (mean $\pm$ SD).

Compare the incident regulator test result to the historical value found above. Then determine the probability that a new regulator in the NEDU RegStat database would have a higher WOB than that of the incident regulator. *(This assumes that the mean and SD for the historically measured regulators are typical for a normally distributed population. Those probabilities can be estimated by finding the tail area probabilities of a normal population with the same mean and SD as the historical database)*. Express that probability as a percent (P%).

For example, if the WOB of the incident regulator had been 1.3 kPa, there would be a probability of 0.174 (P% = 17.4) that a higher WOB would be found by chance among typical new regulators previously tested at NEDU. If the WOB in the incident regulator had been 1.5 kPa, then the probability of finding a higher WOB would have been 0.052 (P% = 5.2). However, for a WOB of 2.24 kPa, that probability would be only 0.000015 (P% = 0.0015). In other words, it is very unlikely that a WOB as high as 2.24 kPa would be found by chance among a mixed group of new regulators. On the following page is a format for presenting

comparison results for tests of incident regulators.

7-2.6 Is calculated WOB correct?

Method 1): Use arbitrarily complex mathematical functions to generate simulated P-V loops. The integral of that function represents the area inside the loop. Dividing by the tidal volume (Vt) yields the "WOB". Apply the computer WOB analysis to the mathematically generated "data" and compare answers.

Method 2): Scan a hard copy P-V loop into a *.TIF format file. Import into SigmaScan and use planimetry to compute the area inside the loop. Divide that area by tidal volume. (If at all possible, scan the original P-V loop, not a copy. Copies are often slightly distorted.)

7-2.7 What if computer files are lost but hard copies of P-V loops exist?

Form TIF format computer graphic files by scanning hard copies of P-V loops with a full page scanner at a resolution of 75 dpi. Import the TIF files into SigmaScan (Version 1.0 for the PC, Jandel Scientific) and trace the outline of the loop using a mouse. SigmaScan can determine the area of the loop by planimetry. Divide the loop area by tidal volume to find "WOB".

Incident Regulator Test Report Format and Example

Incident victim - Case # - Regulator i.d (s).
Date of test

The performance of the above regulator(s) was compared to test results of all new regulators submitted to NEDU for possible Navy use. The new regulator data is expressed as the mean Work of Breathing (WOB) ± 1 SD. The number of tests in the RegStats Database is in parentheses. The far right column is the estimated probability (expressed as a percent) of finding a regulator with a higher WOB.

Reg. #	Depth (msw)	Supply Pressure	WOB (kPa) at 40 RMV	RegStats Database	P%
679319	30	1500 psi	1.42	1.07 ± 0.30 (58)	12
"	50	"	1.71	1.13 ± 0.39 (58)	7
"	60	"	1.80	1.18 ± 0.48 (61)	10
"	30	500	1.55	1.10 ± 0.33 (56)	9
"	50	"	1.90	1.27 ± 0.47 (55)	9
"	60	"	2.38	1.32 ± 0.55 (53)	3
B78508	30	1500	1.54	1.07 ± 0.30 (58)	6
"	50	"	1.73	1.13 ± 0.39 (58)	6
"	60	"	1.76	1.18 ± 0.48 (61)	11
"	30	500	1.62	1.10 ± 0.33 (56)	6
"	50	"	1.75	1.27 ± 0.47 (55)	16
"	60	"	2.12	1.32 ± 0.55 (53)	7

Interpretation

P% can vary from 0 to 100. The larger the P% the better the tested regulator performed relative to new regulators in commercial use. A P% of 10 means that approximately 10% of new regulators tested at NEDU were **more difficult** to breathe than the tested accident regulator.

CHAPTER 8

BREATHING EFFORT CALCULATION

8-1 INTRODUCTION

The following pages are from a document created by MathCad (Version 4.0 for Windows, MathSoft, Inc.) rigorously defining the procedures whereby Work of Breathing and breathing effort are determined. A copy of this document in its interactive form can be obtained free of charge as a computer file from NEDU. The file can be used only on a PC running MathCad 4.0 in Windows.

8-2 DERIVATION AND EXAMPLES

Respiratory frequency (Hz) $f := 0.5\cdot sec^{-1}$

Period (sec) $T := \frac{1}{f}$

Sample rate $s := 1000\cdot sec^{-1}$

Sample interval $\Delta T := \frac{1}{s}$ $\quad \Delta T = 0.001\cdot sec$

Number of samples

$n := T\cdot s \qquad n = 2\cdot 10^{3}$

Angular frequency

$\omega := 2\cdot\pi\cdot f \qquad \omega = 3.142\cdot sec^{-1}$

Sample sequence

$i := 1 .. (n-1)$

$t_i := i\cdot\Delta T$ ... time at each sampling period

$kPa \equiv 1000\cdot Pa$ ... definition

$tnd_i := t_i\cdot sec^{-1}$ ... non-dimensional form for time (for graphing purposes)

UBA Resistance

$R := 0.5\cdot kPa\cdot\frac{sec}{liter}$

UBA Elastance

$E := 0\cdot\frac{kPa}{liter}$

Tidal Volume

$Vt := 3\cdot liter \qquad Vtnd := Vt\cdot liter^{-1}$

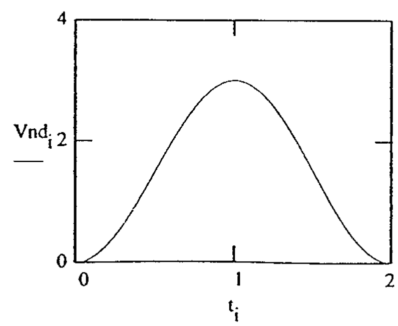
Volume - as a function of time

$V(t) := Vt\cdot\sin\left(\frac{\omega}{2}\cdot t\right)^{2}$

$V_i := Vt\cdot\sin\left(\frac{\omega}{2}\cdot t_i\right)^{2}$ ... Volume at each sampling period

$Vnd_i := V_i\cdot liter^{-1}$

Volume tracing



Flow - the time derivative of volume:

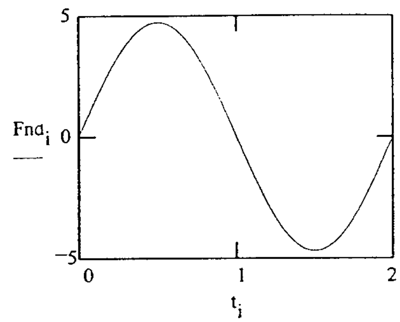
$F(t) := \frac{d}{dt}V_t$

$F(t) := \omega\cdot Vt\cdot\sin\left(\frac{1}{2}\cdot\omega\cdot t\right)\cdot\cos\left(\frac{1}{2}\cdot\omega\cdot t\right)$

From a trigonometric identity this is equivalent to:

$F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$ $\quad F_i := \frac{\omega}{2} \cdot Vt \cdot \sin\left(\omega \cdot t_i\right)$ ... discrete samples of flow at various sampling intervals

$Fnd_i := F_i \cdot liter^{-1} \cdot sec$ ... non-dimensional form

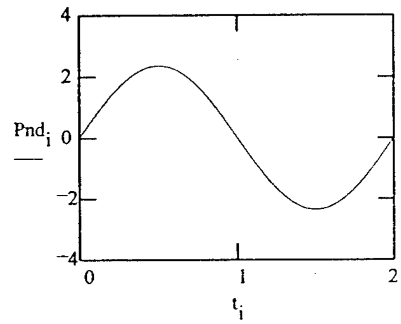


Pressure

$$Pm(t) := R \cdot \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t) + E \cdot \left(Vt \cdot \sin\left(\frac{\omega}{2} \cdot t\right)^2\right)$$

$$P_i := R \cdot F_i + E \cdot V_i$$

$$Pnd_i := P_i \cdot kPa^{-1}$$



$\max(P) = 2.356 \cdot kPa$ ... maximum pressure

$\text{mean}(P) = 0 \cdot kPa$ ... average pressure

$\min(P) = -2.356 \cdot kPa$ ... minimum pressure

Time-Averaged Pressure - Full Cycle

To integrate we must non-dimensionalize (a peculiarity of MathCad):

$T := T \cdot sec^{-1}$ $\quad \omega := \omega \cdot sec$ $\quad Vt := Vt \cdot liter^{-1}$

$R := R \cdot liter \cdot (kPa \cdot sec)^{-1}$

$Pm(t) := R \cdot \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$ $\quad F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$

$\frac{1}{T} \cdot \int_0^T Pm(t)\, dt = 0$ ... time-averaged pressure for a full cycle

$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} Pm(t)\, dt = 1.5$ ... time-averaged pressure for one-half cycle

Another type of time-averaged pressure is called:

Root Mean Square pressure (Prms) or Effective Pressure

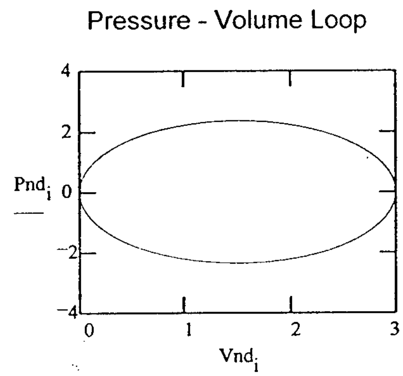
$$\text{Prms} := \sqrt{\frac{1}{T}\cdot\int_0^T \text{Pm}(t)^2\,dt} \qquad \text{Prms} = 1.666$$ ... for a full breathing cycle

Another way of expressing Prms is: $$\text{Prms} := \sqrt{\frac{1}{n}\cdot\sum_i {P_i}^2} \qquad \text{Prms} = 1.666\cdot\text{kPa}$$

Periodically oscillating waveforms are typically described in terms of their RMS values. For example, 110 v is an RMS value for household voltage.

Pressure-Volume Loops

The area inside the pressure-volume loop is defined as the **Work of Breathing**, with units of Joules (J).



Work of Breathing

$$W := \int_0^T \text{Pm}(t)\cdot F(t)\,dt \qquad W = 11.103$$ Note:F(t) = dV/dt

In diving it has become customary to divide W by tidal volume. This results is a volume - averaged pressure (Pva). We refer to this average pressure as a measure of resistive breathing effort.

Resistive Effort

$$\text{Pva} := \frac{1}{\text{Vt}}\cdot\int_0^T \text{Pm}(t)\cdot F(t)\,dt \qquad \text{Pva} = 3.701$$

Closed-Circuit UBA have ELASTANCE

Respiratory frequency (Hz) $f := 0.5\cdot sec^{-1}$

Period (sec) $T := \frac{1}{f}$

Sample rate $s := 1000\cdot sec^{-1}$

Sample interval $\Delta T := \frac{1}{s}$ $\quad \Delta T = 0.001\cdot sec$

Angular frequency

$\omega := 2\cdot\pi\cdot f \qquad \omega = 3.142\cdot sec^{-1}$

Sample sequence

$i := 1..(n-1)$

$t_i := i\cdot\Delta T$ ... time at each sampling period

$tnd_i := t_i\cdot sec^{-1}$ ... non-dimensional form for time (for graphing purposes)

UBA Resistance

$R := 0.5\cdot kPa\cdot\frac{sec}{liter}$

UBA Elastance

$E := 1\cdot\frac{kPa}{liter}$

Tidal Volume

$Vt := 3\cdot liter \qquad Vtnd := Vt\cdot liter^{-1}$

Volume - as a function of time

$V(t) := Vt\cdot\sin\left(\frac{\omega}{2}\cdot t\right)^2 \qquad V_i := Vt\cdot\sin\left(\frac{\omega}{2}\cdot t_i\right)^2$ ... Volume at each sampling period

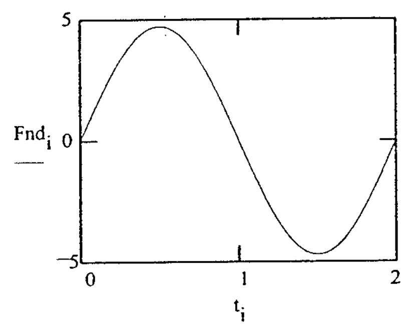
$Vnd_i := V_i\cdot liter^{-1}$

Flow - the time derivative of volume:

$F(t) := \frac{\omega}{2}\cdot Vt\cdot\sin(\omega\cdot t) \qquad F_i := \frac{\omega}{2}\cdot Vt\cdot\sin\left(\omega\cdot t_i\right)$

$Fnd_i := F_i\cdot liter^{-1}\cdot sec$ ... non-dimensional form

Flow Tracing



Pressure

$Pm(t) := R\cdot\frac{\omega}{2}\cdot Vt\cdot\sin(\omega\cdot t) + E\cdot\left(Vt\cdot\sin\left(\frac{\omega}{2}\cdot t\right)^2\right)$

$P_i := R\cdot F_i + E\cdot V_i$

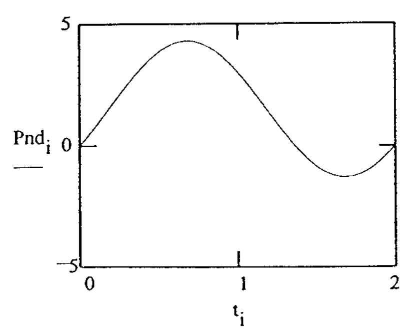
$Pnd_i := P_i\cdot kPa^{-1}$

$max(P) = 4.293\cdot kPa$ ... maximum pressure

$mean(P) = 1.5\cdot kPa$ ... average pressure

$min(P) = -1.293\cdot kPa$ ... minimum pressure

Pressure Tracing



Time-Averaged Pressure - Full Cycle

$T := T \cdot sec^{-1}$ $\qquad \omega := \omega \cdot sec$ $\qquad Vt := Vt \cdot liter^{-1}$

$R := R \cdot liter \cdot (kPa \cdot sec)^{-1}$ $\qquad E := E \cdot kPa^{-1} \cdot liter$

$$Pm(t) := R \cdot \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t) + E \cdot \left(Vt \cdot \sin\left(\frac{\omega}{2} \cdot t\right)\right)^2 \qquad F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$$

$\frac{1}{T} \cdot \int_0^T Pm(t)\, dt = 1.5$ ... time-averaged pressure for a full cycle

$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} Pm(t)\, dt = 3$ ... time-averaged pressure for one-half cycle

RMS Pressure

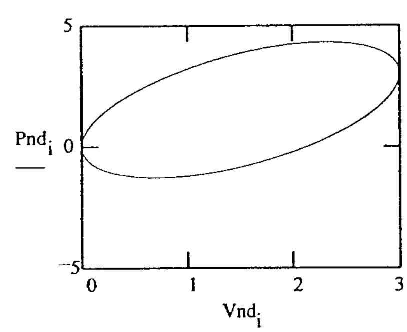
$Prms := \sqrt{\frac{1}{T} \cdot \int_0^T Pm(t)^2\, dt}$ $\qquad Prms = 2.48$ ... for a full breathing cycle

Or ...

$Prms := \sqrt{\frac{1}{n} \cdot \sum_i {P_i}^2}$ $\qquad Prms = 2.48 \cdot kPa$

*All time-based pressures are **changed** by elastance (see previous example).*

Pressure - Volume Loop



Work of Breathing

$W := \int_0^T Pm(t) \cdot F(t)\, dt$ $\qquad W = 11.103$

Resistive Effort

$Pva := \frac{1}{Vt} \cdot \int_0^T Pm(t) \cdot F(t)\, dt$ $\qquad Pva = 3.701$

*Work of Breathing and Resistive Effort (a volume-averaged pressure) are **unchanged** by simple elastance.*

If **resistance is minimal**, but elastance is still present, then:

Respiratory frequency (Hz) $f := 0.5\cdot \mathrm{sec}^{-1}$

Period (sec) $T := \frac{1}{f}$

Sample rate $s := 1000\cdot \mathrm{sec}^{-1}$

Sample interval $\Delta T := \frac{1}{s}$ $\quad \Delta T = 0.001 \cdot \mathrm{sec}$

Angular frequency

$\omega := 2\cdot\pi\cdot f \qquad \omega = 3.142 \cdot \mathrm{sec}^{-1}$

Sample sequence

$i := 1..(n-1)$

$t_i := i\cdot\Delta T$ ... time at each sampling period

$tnd_i := t_i\cdot \mathrm{sec}^{-1}$ ... non-dimensional form for time (for graphing purposes)

UBA Resistance

$R := 0\cdot \mathrm{kPa}\cdot\frac{\mathrm{sec}}{\mathrm{liter}}$

UBA Elastance

$E := 1\cdot\frac{\mathrm{kPa}}{\mathrm{liter}}$

Tidal Volume

$Vt := 3\cdot \mathrm{liter} \qquad Vtnd := Vt\cdot \mathrm{liter}^{-1}$

Volume - as a function of time

$V(t) := Vt\cdot \sin\left(\frac{\omega}{2}\cdot t\right)^2$

$V_i := Vt\cdot \sin\left(\frac{\omega}{2}\cdot t_i\right)^2$ ... Volume at each sampling period

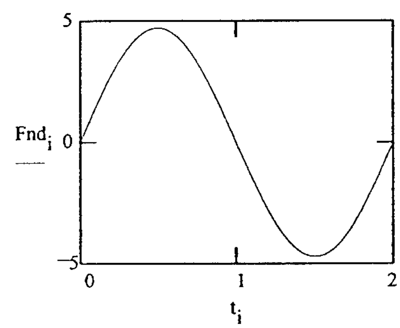
$Vnd_i := V_i\cdot \mathrm{liter}^{-1}$

Flow - the time derivative of volume:

$F(t) := \frac{\omega}{2}\cdot Vt\cdot \sin(\omega\cdot t) \qquad F_i := \frac{\omega}{2}\cdot Vt\cdot \sin\left(\omega\cdot t_i\right)$

$Fnd_i := F_i\cdot \mathrm{liter}^{-1}\cdot \mathrm{sec}$ ... non-dimensional form

Flow Tracing



Pressure

$Pm(t) := R\cdot\frac{\omega}{2}\cdot Vt\cdot \sin(\omega\cdot t) + E\cdot \left(Vt\cdot \sin\left(\frac{\omega}{2}\cdot t\right)^2\right)$

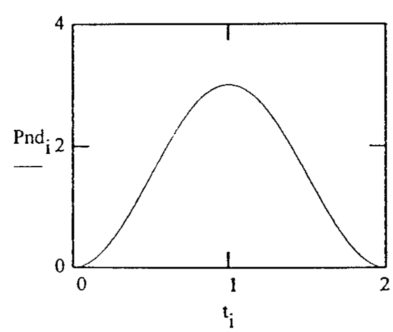
$P_i := R\cdot F_i + E\cdot V_i \qquad Pnd_i := P_i\cdot \mathrm{kPa}^{-1}$

$\max(P) = 3 \cdot \mathrm{kPa}$ ... maximum pressure

$\mathrm{mean}(P) = 1.5 \cdot \mathrm{kPa}$ ... average pressure

$\min(P) = 0 \cdot \mathrm{kPa}$ ... minimum pressure

Pressure Tracing



Time-Averaged Pressure - Full Cycle

$T := T \cdot sec^{-1} \qquad \omega := \omega \cdot sec \qquad Vt := Vt \cdot liter^{-1}$

$R := R \cdot liter \cdot (kPa \cdot sec)^{-1} \qquad E := E \cdot kPa^{-1} \cdot liter$

$$Pm(t) := R \cdot \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t) + E \cdot \left(Vt \cdot \sin\left(\frac{\omega}{2} \cdot t\right) \right)^2 \qquad F(t) := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t)$$

$$\frac{1}{T} \cdot \int_0^T Pm(t)\,dt = 1.5$$ ... time-averaged pressure for a full cycle

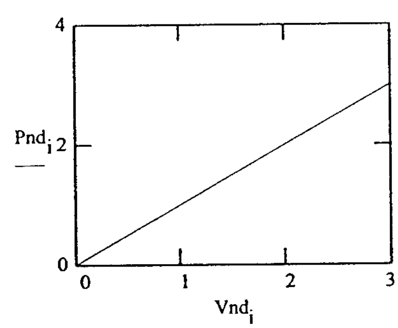
$$\frac{2}{T} \cdot \int_0^{\frac{T}{2}} Pm(t)\,dt = 1.5$$ ... time-averaged pressure for one-half cycle

RMS Pressure

$$Prms := \sqrt{\frac{1}{T} \cdot \int_0^T Pm(t)^2\,dt} \qquad Prms = 1.837$$ ... for a full breathing cycle

Pressures are considerable. However, as seen below, conventional measures of work and volume-averaged pressure (resistive effort) are negligibly small.

Pressure - Volume Loop



Work of Breathing

$$W := \int_0^T Pm(t) \cdot F(t)\,dt \qquad W = 0$$

Resistive Effort

$$Pva := \frac{1}{Vt} \cdot \int_0^T Pm(t) \cdot F(t)\,dt \qquad Pva = 0$$

Does this mean that no work or effort is required to repeatibly inflate and deflate an elastic balloon, or a breathing bag immersed in water? Experience tells us otherwise! For that reason, **Prms is a physiologically relevant characteristic of UBA.**

The Summation Approximation

To simulate complex regulator function, we have to use non-integrable logical functions. For these we use summations instead of integrals.

To express work as a summation we must define the inspiratory and expiratory phases of respiration, and determine the change in volume occuring during each sampling interval. We use as an example the original resistive UBA without elastance.

$T := T \cdot sec \qquad Vt := Vt \cdot liter \qquad \omega := \omega \cdot sec^{-1}$ ... this reestablishes dimensions

$R := 0.5 \cdot \frac{kPa}{liter} \cdot sec \qquad E := 0 \cdot \frac{kPa}{liter}$ ... resistive UBA without elastance

$F_i := \frac{\omega}{2} \cdot Vt \cdot \sin(\omega \cdot t_i) \qquad V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2 \qquad P_i := R \cdot F_i + E \cdot V_i$

$Pmin := |\min(P)| \qquad Pmin = 2.356 \cdot kPa$ ... definition of minimum pressure

$Prms := \sqrt{\frac{1}{n} \cdot \sum_i \left(P_i\right)^2} \qquad Prms = 1.666 \cdot kPa$

Expiratory Work

$i := 1 .. \frac{n}{2} \qquad t_i := i \cdot \Delta T$

$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$ ... Volume at each sampling interval

$\Delta V_i := V_i - V_{(i-1)}$ ... Volume increment for each sampling interval

The work of breathing for the expiratory side of the loop is found by the trapezoidal rule:

$A1 := \sum_i \left[\left(P_i + Pmin\right) \cdot \Delta V_i\right] \qquad A1 = 12.62 \cdot joule$

Inspiratory Work - the above is repeated except that $i := \frac{n}{2} + 1 .. (n-1)$

$t_i := i \cdot \Delta T$

$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$ ... Volume at each sampling interval

$\Delta V_i := V_{(i-1)} - V_i$ ... Volume increment for each sampling interval

The work of breathing for the inspiratory side of the loop is:

$$A2 := \sum_i \left[P_i + Pmin \cdot \Delta V_i \right] \qquad A2 = 1.517 \cdot \text{joule}$$

Total Work of Breathing is thus equal to A1 - A2 $\quad W := A1 - A2$

$W = 11.103 \cdot \text{joule}$ ... This application of the trapezoidal rule yields a result which differs slightly from the previous integration. The result can be made more exact by increasing the sampling rate; i.e. by taking more data points per breath.

If we follow the diving convention of dividing W by Vt, we obtain a pressure.

$$\frac{W}{Vt} = 3.701 \cdot \text{kPa}$$

Although there is no advantage in doing so, we can also express this quotient as:

$$\frac{W}{Vt} = 3.701 \cdot \frac{\text{joule}}{\text{liter}}$$

... **joule/liter and kPa are equivalent units**

For that reason we refer to W/Vt as Pva (Pressure, volume-averaged) $\quad Pva := \frac{W}{Vt}$

For a ***resistive UBA without elastance,*** *Prms is mathematically related to Pva and true Work of Breathing (W) by:*

$$Pva := \frac{Prms^2 \cdot T}{R \cdot Vt} \qquad Pva = 3.701 \cdot \text{kPa}$$

$$W := \frac{Prms^2 \cdot T}{R} \qquad W = 11.103 \cdot \text{joule}$$

Fourier Superposition - a method for defining complicated waveforms:

$i := 1 .. (n-1)$

$P_i := 1.1 \cdot R \cdot \frac{\omega}{2} \cdot Vt \cdot \left(\sin(\omega \cdot t_i) + 0.28 \cdot \sin(3 \cdot \omega \cdot t_i) + 0.1 \cdot \sin(5 \cdot \omega \cdot t_i) \right)$

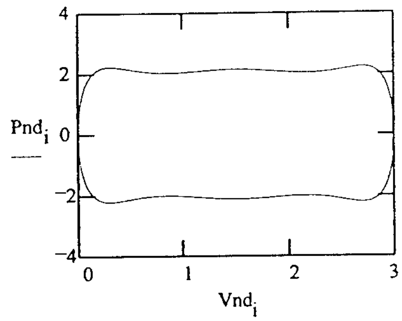
$Pnd_i := P_i \cdot kPa^{-1}$

$max(P) = 2.215 \cdot kPa$

$mean(P) = 0 \cdot kPa$

$min(P) = -2.215 \cdot kPa$

$Prms := \sqrt{\frac{1}{n} \cdot \sum_i (P_i)^2}$ $\qquad Prms = 1.912 \cdot kPa$



Expiratory Work of Breathing

$i := 1 .. \frac{n}{2}$ $\qquad t_i := i \cdot \Delta T$

$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$ ... Volume at each sampling interval

$\Delta V_i := V_i - V_{(i-1)}$ ... Volume increment for each sampling interval

$A1 := \sum_i \left[(P_i + Pmin) \cdot \Delta V_i \right]$ $\qquad A1 = 13.175 \cdot joule$

Inspiratory Work

$i := \left(\frac{n}{2} + 1\right) .. (n-1)$ $\qquad t_i := i \cdot \Delta T$

$V_i := Vt \cdot \sin\left(\frac{\omega}{2} \cdot t_i\right)^2$ ... Volume at each sampling interval

$\Delta V_i := V_{(i-1)} - V_i$ ... Volume increment for each sampling interval

$A2 := \sum_i \left[(P_i + Pmin) \cdot \Delta V_i \right]$ $\qquad A2 = 0.962 \cdot joule$

Total Work of Breathing

$W := A1 - A2$ $\qquad W = 12.214 \cdot joule$

Resistive Effort

$Pva := \frac{W}{Vt}$ $\qquad Pva = 4.071 \cdot kPa$

For this wave form, maximum and minimum pressures are slightly lower than the sinusoidal case, but work and resistance is higher.

We can also simulate a
Venturi-assisted Regulator

$i := 0..(n - 1)$

$E_i := R\cdot\frac{\omega}{2}\cdot Vt\cdot\ \sin\ \omega\cdot t_i\ + 0.2\cdot\sin\ 3\cdot\omega\cdot t_i\ + 0.1\cdot\sin\ 5\cdot\omega\cdot t_i\ + 0.1\cdot\sin\ 27\cdot\omega\cdot t_i\ + 0.1\cdot rnd(2)$

$I_i := E_i - R\cdot\frac{\omega}{2}\cdot Vt\cdot\ 1.2\cdot\sin\ \omega\cdot t_i\ - 0.35\cdot\sin\ 3\cdot\omega\cdot t_i\ - .02\cdot rnd(3)$

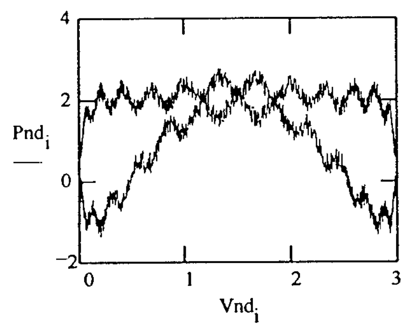
$P_i := \text{if } i<\frac{n}{2}, E_i, I_i$ $\qquad$ $Pnd_i := P_i\cdot kPa^{-1}$

$\max(P) = 2.788\cdot kPa$

$\text{mean}(P) = 1.081\cdot kPa$

$\min(P) = -1.38\cdot kPa$

$Prms := \sqrt{\frac{1}{n}\cdot\sum_i P_i^{\ 2}}$ $\qquad$ $Prms = 1.563\cdot kPa$



Expiratory Work of Breathing

$i := 1..\frac{n}{2}$ $\qquad$ $t_i := i\cdot\Delta T$

$V_i := Vt\cdot\sin\ \frac{\omega}{2}\cdot t_i^{\ \ 2}$ $\qquad$ ... Volume at each sampling interval

$\Delta V_i := V_i - V_{(i-1)}$ $\qquad$ ... Volume increment for each sampling interval

$A1 := \sum_i \left[\ P_i + Pmin\ \cdot\Delta V_i\right]$ $\qquad$ $A1 = 13.322\cdot joule$

Inspiratory Work

$i := \ \frac{n}{2} + 1\ \ ..(n - 1)$ $\qquad$ $t_i := i\cdot\Delta T$

$V_i := Vt\cdot\sin\ \frac{\omega}{2}\cdot t_i^{\ \ 2}$ $\qquad$ ... Volume at each sampling interval

$\Delta V_i := V_{(i-1)} - V_i$ $\qquad$ ... Volume increment for each sampling interval

$A2 := \sum_i \left[\ P_i + Pmin\ \cdot\Delta V_i\right]$ $\qquad$ $A2 = 9.085\cdot joule$

Total Work of Breathing $\qquad$ $W := A1 - A2$ $\qquad$ $W = 4.238\cdot joule$

Resistive Effort $\qquad$ $Pva := \frac{W}{Vt}$ $\qquad$ $Pva = 1.413\cdot kPa$

Chattering Regulator

$i := 0 .. (n - 1)$

$E_i := R \cdot \frac{\omega}{2} \cdot Vt \cdot \ \sin\ \omega \cdot t_i \ + 0.2 \cdot \sin\ 3 \cdot \omega \cdot t_i \ + 0.001 \cdot \sin\ 5 \cdot \omega \cdot t_i \ + 0.05 \cdot \sin\ 27 \cdot \omega \cdot t_i \ + 0.001 \cdot \mathrm{rnd}(2)$

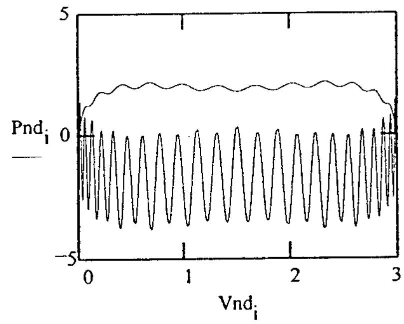
$I_i := E_i - R \cdot \frac{\omega}{2} \cdot Vt \cdot \ 0.1 \cdot \sin\ \omega \cdot t_i \ + 0.8 \cdot \sin\ 49 \cdot \omega \cdot t_i \ - .0002 \cdot \mathrm{rnd}(3)$

$P_i := \mathrm{if}\ i < \frac{n}{2}, E_i, I_i$ $\qquad$ $Pnd_i := P_i \cdot kPa^{-1}$

$\max(P) = 2.17 \cdot kPa$

$\mathrm{mean}(P) = 0.09 \cdot kPa$

$\min(P) = -3.849 \cdot kPa$



$Prms := \sqrt{\frac{1}{n} \cdot \sum_i P_i^{\ 2}}$ $\qquad$ $Prms = 1.876 \cdot kPa$

Expiratory Work of Breathing

$i := 1 .. \frac{n}{2}$ $\qquad$ $t_i := i \cdot \Delta T$

$V_i := Vt \cdot \sin\ \frac{\omega}{2} \cdot t_i^{\ 2}$ $\qquad$ ... Volume at each sampling interval

$\Delta V_i := V_i - V_{(i-1)}$ $\qquad$ ... Volume increment for each sampling interval

$A1 := \sum_i \left[\ P_i + Pmin \ \cdot \Delta V_i\right]$ $\qquad$ $A1 = 12.627 \cdot joule$

Inspiratory Work

$i := \frac{n}{2} + 1 \ .. (n - 1)$ $\qquad$ $t_i := i \cdot \Delta T$

$V_i := Vt \cdot \sin\ \frac{\omega}{2} \cdot t_i^{\ 2}$ $\qquad$ ... Volume at each sampling interval

$\Delta V_i := V_{(i-1)} - V_i$ $\qquad$ ... Volume increment for each sampling interval

$A2 := \sum_i \left[\ P_i + Pmin \ \cdot \Delta V_i\right]$ $\qquad$ $A2 = 2.081 \cdot joule$

Total Work of Breathing $\qquad$ $W := A1 - A2$ $\qquad$ $W = 10.546 \cdot joule$

Resistive Effort $\qquad$ $Pva := \frac{W}{Vt}$ $\qquad$ $Pva = 3.515 \cdot kPa$

Super-Venturi Regulator

$i := 0..(n-1)$

$E_i := R\cdot\frac{\omega}{2}\cdot Vt\cdot\ \sin\ \omega\cdot t_i\ + 0.2\cdot\sin\ 3\cdot\omega\cdot t_i\ + 0.1\cdot\sin\ 5\cdot\omega\cdot t_i\ + 0.1\cdot\sin\ 27\cdot\omega\cdot t_i\ + 0.1\cdot rnd(2)$

$I_i := E_i - R\cdot\frac{\omega}{2}\cdot Vt\cdot\ 1.2\cdot\sin\ \omega\cdot t_i\ - 1.0\cdot\sin\ 3\cdot\omega\cdot t_i\ - .0002\cdot rnd(3)$

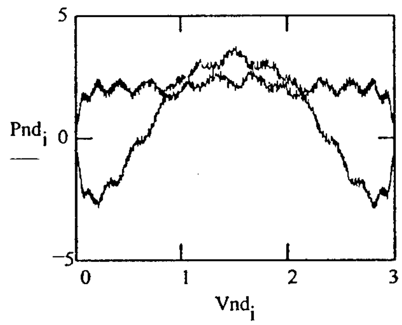
$P_i := \text{if } i<\frac{n}{2}, E_i, I_i$ $\qquad$ $Pnd_i := P_i\cdot kPa^{-1}$

$max(P) = 3.756\cdot kPa$

$mean(P) = 0.89\cdot kPa$

$min(P) = -2.923\cdot kPa$

$Prms := \sqrt{\frac{1}{n}\cdot\sum_i P_i^{\ 2}}$ $\qquad$ $Prms = 1.985\cdot kPa$



Expiratory Work of Breathing

$i := 1..\frac{n}{2}$ $\qquad$ $t_i := i\cdot\Delta T$

$V_i := Vt\cdot\sin\left(\frac{\omega}{2}\cdot t_i\right)^2$ ... Volume at each sampling interval

$\Delta V_i := V_i - V_{(i-1)}$ ... Volume increment for each sampling interval

$A1 := \sum_i\left[\ P_i + Pmin\ \cdot\Delta V_i\right]$ $\qquad$ $A1 = 13.366\cdot joule$

Inspiratory Work

$i := \ \frac{n}{2} + 1\ \ ..(n-1)$ $\qquad$ $t_i := i\cdot\Delta T$

$V_i := Vt\cdot\sin\left(\frac{\omega}{2}\cdot t_i\right)^2$ ... Volume at each sampling interval

$\Delta V_i := V_{(i-1)} - V_i$ ... Volume increment for each sampling interval

$A2 := \sum_i\left[\ P_i + Pmin\ \cdot\Delta V_i\right]$ $\qquad$ $A2 = 8.877\cdot joule$

Total Work of Breathing $\qquad$ $W := A1 - A2$ $\qquad$ $W = 4.489\cdot joule$

Resistive Effort $\qquad$ $Pva := \frac{W}{Vt}$ $\qquad$ $Pva = 1.496\cdot kPa$

REFERENCES

1. Middleton, J.R. and Thalmann, E.D., Standardized NEDU unmanned UBA test procedures and performance goals, NEDU Report 3-81. U.S. Navy Experimental Diving Unit, Panama City, FL, 1981.

2. Principe, J.C., Smith, J.R., SAMICOS- A sleep analyzing microcomputer system. *IEEE Transactions on Biomedical Engineering*, Vol. BME-33, NO. 10, October, 1986.

3. Knafelc, M.E., Unmanned and manned evaluation of a prototype closed-circuit underwater breathing apparatus, the Ex-19, NEDU Report 5-88. U.S. Navy Evperimental Diving Unit, Panama City, FL, 1988.

4. Fink, D.G. and D. Christiansen, Eds., Electronics Engineers' Handbook, 3rd Ed., McGraw-Hill Book Company, New York, 1989.

5. Fitzgerald, A.E., D.E. Higginbotham, and A. Grabel, Basic Electrical Engineering, McGraw-Hill Book Company, New York, 1967.

6. Otis, A.B., The Work of Breathing, In: Handbook of Physiology, Sect. 3 Respiration, Vol. 1, W. Fenn and H. Rahn, Eds., American Physiological Society, Washington, pp: 463-476, 1964.

7. Lanphier, E.H. and E.M. Camporesi, Respiration and Exertion, 4th Ed., In: The Physiology and Medicine of Diving, P.B. Bennett and D.H. Elliott, eds, W.B. Saunders Co.., London, 1993.

8. Taylor, N.A.S. and J.B. Morrison, Lung centroid pressure in immersed man. *Undersea Biomedical Research*, vol. 16, pp.3-19, 1989.

9. Clarke, J.R, Optimal hydrostatic loading for closed-circuit underwater breathing apparatus, NMRI Report 91-08, 1991.

10. Carlson, N, J.R. Clarke, and E.T. Flynn, The effects of hydrostatic loading during immersion on oxygen uptake and ventilatory endurance. *Undersea Biomedical Research* 16: Suppl., 1989.

11. Joye, D.D., J.R. Clarke, N.A. Carlson, and E.D. Thalmann, Characterization and measurment of elastance with application to underwater breathing apparatus, *Undersea and Hyperbaric Medicine* 21:53-65, 1994.

12. Fishman, A.P., L.E. Farhi, S.M. Tenney, Eds, Handbook of Physiology, Section 3: The Respiratory System, Volume IV. Gas Exchange, American Physiological Society, Bethesda, 1987.

13. Powers, S.K., W. Riley, and E.T. Howley, Comparison of fat metabolism between trained

men and women during prolonged aerobic work. *Res. Quart. for Ex. and Sport* 51(2): 427-431, 1980.

14. E. Jansson, On the significance of the respiratory exchange ratio after different diets during exercise in man, *Acta Physiol. Scand.*, 114:103, 1982.

15. Fagraeus, L., Cardiorespiratory and metabolic functions during exercise in the hyperbaric environment. *Acta. Physiol. Scand.* Suppl. 414, 1974a.

16. Lundgren, C, Biomedical criteria for optimal elastic resistance in divers' underwater breathing apparatus, Final Report, NMRDC Project N0001489J1702, 1993.

17. Clarke, J.R., Impedance and power measurements in the testing of closed circuit UBA. In: Lung Physiology and Divers' Breathing Apparatus, eds. Flook and Brubakk, SINTEF UNIMED, Aberdeen, pp: 85-99, 1992.

18. Altman, N.S., Introduction to Kernel and Nearest-Neighbor Nonparametric Regression, *The American Statistician*, Aug, 1992.

19. Burr, I.W. Elementary Statistical Quality Control, Marcel Dekker, Inc., New York, 1979.

20. McClave, J.T. and P.G. Benson, A First Course in Business Statistics, 5th ed., MacMillan Publishing Co., New York, 1992.

APPENDIX A: ALARM LOGIC SOFTWARE

The icon-based software used to create the evaluation algorithm is Workbench 2.1 (Strawberry Tree, Braintree, MA.) running on a Macintosh SI microcomputer. Flow of logic is from left to right and is indicated by the connecting lines on the worksheet (Figure A1).

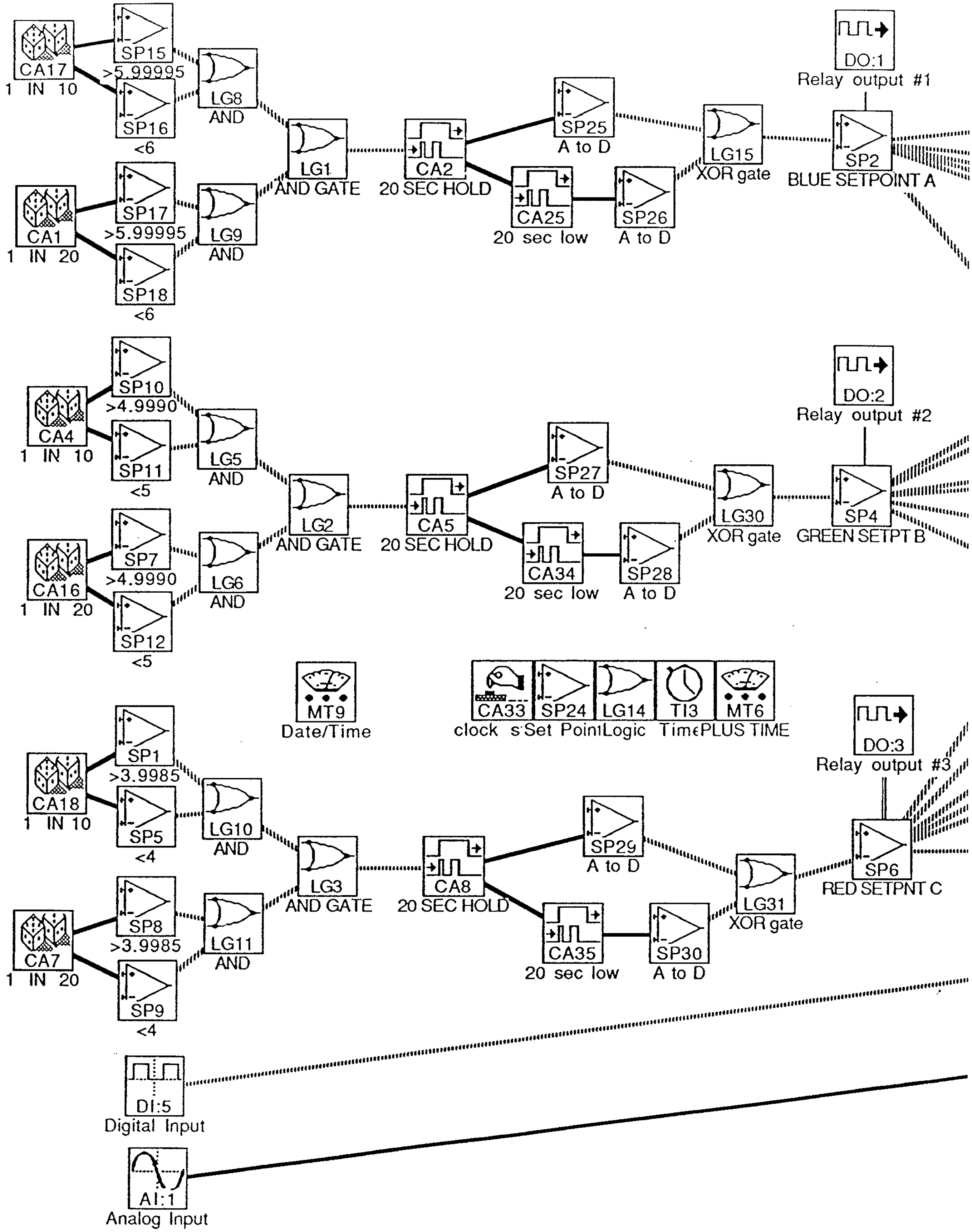
Random number generators create three pulse trains representing signals from the UBA's three oxygen sensors. These pulses are sent through a setpoint filter with logical AND gates to narrow the bandwidth of positive responses. This action limits the frequency of the sensor dropout pulses; i.e. changes the probability of a simulated sensor failure. Whenever all positive response conditions are satisfied, a "high" state is set and maintained for a period determined by the logic being tested. This "high" state is seen by the UBA being tested as a sensor failure, and thus should be sensed by the alarm logic.

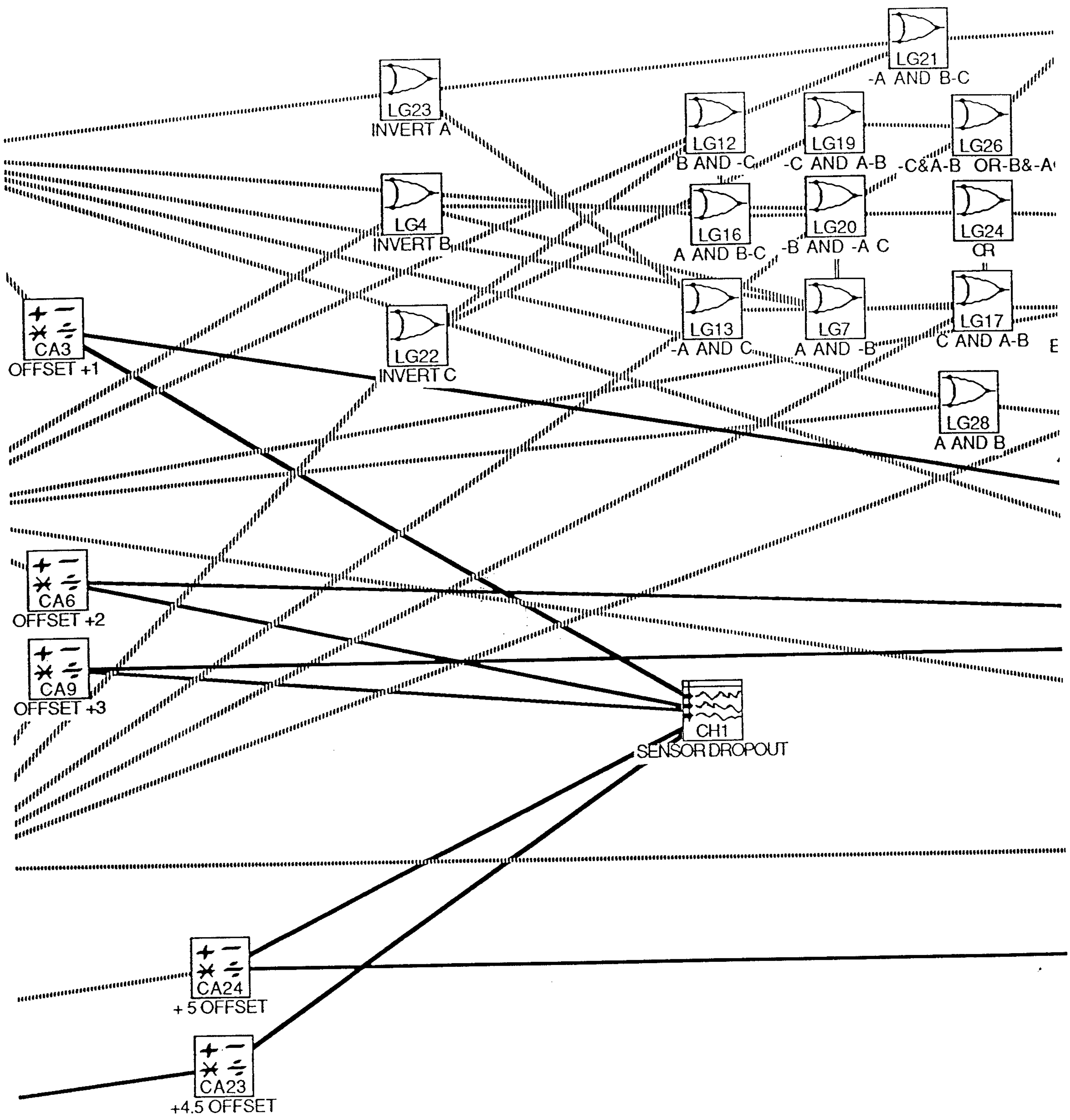
The next set of logic operations insures that the pulse remains in the low state for a minimal time after the "high" state has expired. This waiting time allows the UBA to detect the reset condition. The three signals are then offset from one another to avoid overlap when sent to a tracking chart (Figure A2).

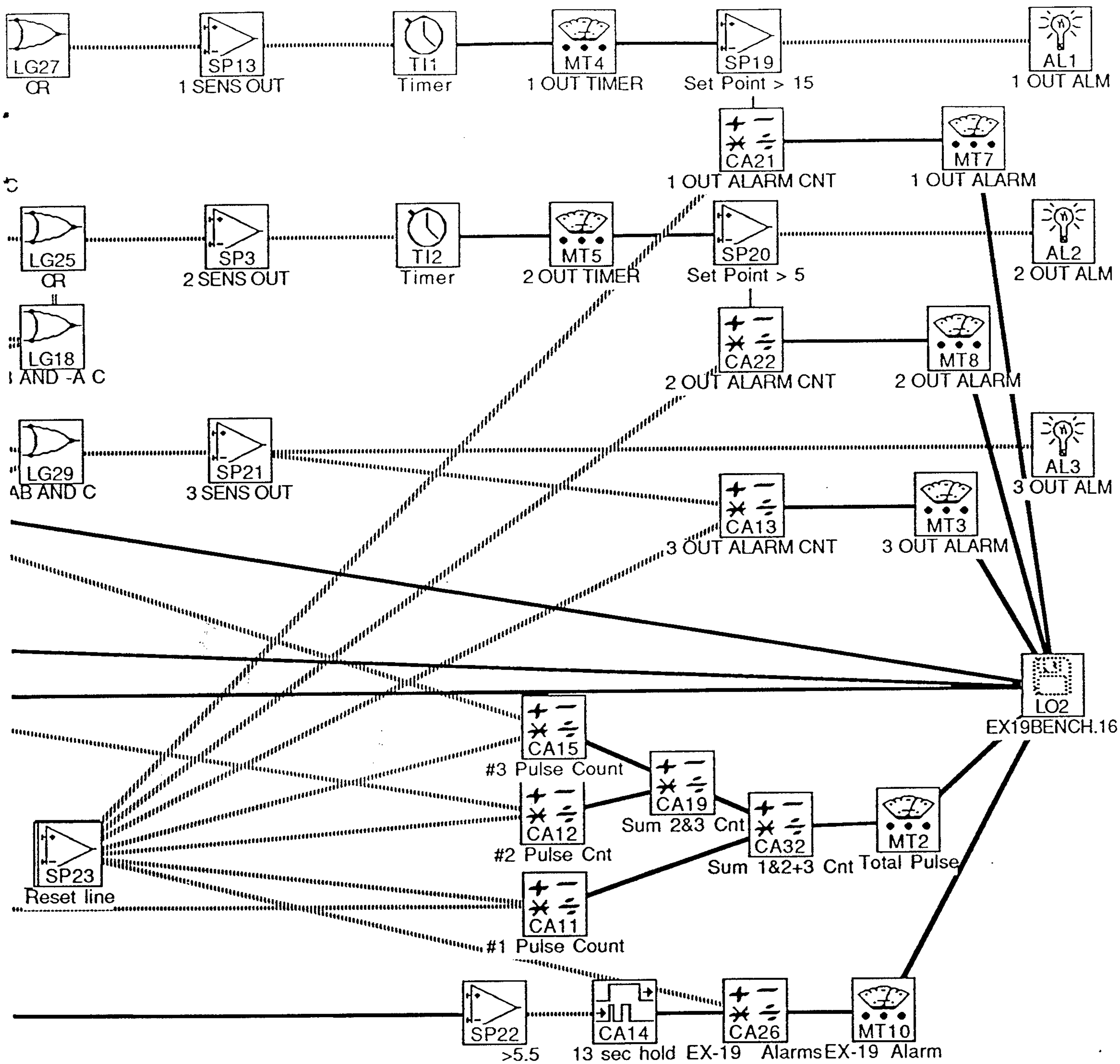
Next, three sets of logic accumulators tabulate the occurrences of one, two, and three simultaneous sensor dropouts. Individual timers monitor these conditions. Total pulse count is recorded and a reset button exists to clear the count on all meters.

Feedback from the UBA being tested is received in both digital and analog form. These data are tabulated as the response to imposed conditions, and compared to the anticipated response for the pass/fail decision. All pertinent data are routed to a log and recorded throughout the test duration at a rate appropriate to the UBA update speed.

Figure A1. Macintosh Evaluation Algorithm for Alarm Logic Test.




LG21
-A AND B-C
LG23
INVERT A
LG12
B AND -C
LG19
-C AND A-B
LG26
-C&A-B OR-B&-A
LG4
INVERT B
LG16
A AND B-C
LG20
-B AND -A C
LG24
OR
CA3
OFFSET +1
LG13
-A AND C
LG7
A AND -B
LG17
C AND A-B
LG22
INVERT C
LG28
A AND B
CA6
OFFSET +2
CA9
OFFSET +3
CH1
SENSOR DROPOUT
CA24
+ 5 OFFSET
CA23
+4.5 OFFSET



LG27
OR
SP13
1 SENS OUT
TI1
Timer
MT4
1 OUT TIMER
SP19
Set Point > 15
AL1
1 OUT ALM
CA21
1 OUT ALARM CNT
MT7
1 OUT ALARM
LG25
OR
SP3
2 SENS OUT
TI2
Timer
MT5
2 OUT TIMER
SP20
Set Point > 5
AL2
2 OUT ALM
LG18
AND -A C
CA22
2 OUT ALARM CNT
MT8
2 OUT ALARM
LG29
AB AND C
SP21
3 SENS OUT
AL3
3 OUT ALM
CA13
3 OUT ALARM CNT
MT3
3 OUT ALARM
LO2
EX19BENCH.16
CA15
#3 Pulse Count
CA19
Sum 2&3 Cnt
CA12
#2 Pulse Cnt
CA32
Sum 1&2+3 Cnt
MT2
Total Pulse
SP23
Reset line
CA11
#1 Pulse Count
SP22
>5.5
CA14
13 sec hold
CA26
EX-19 Alarms
MT10
EX-19 Alarm

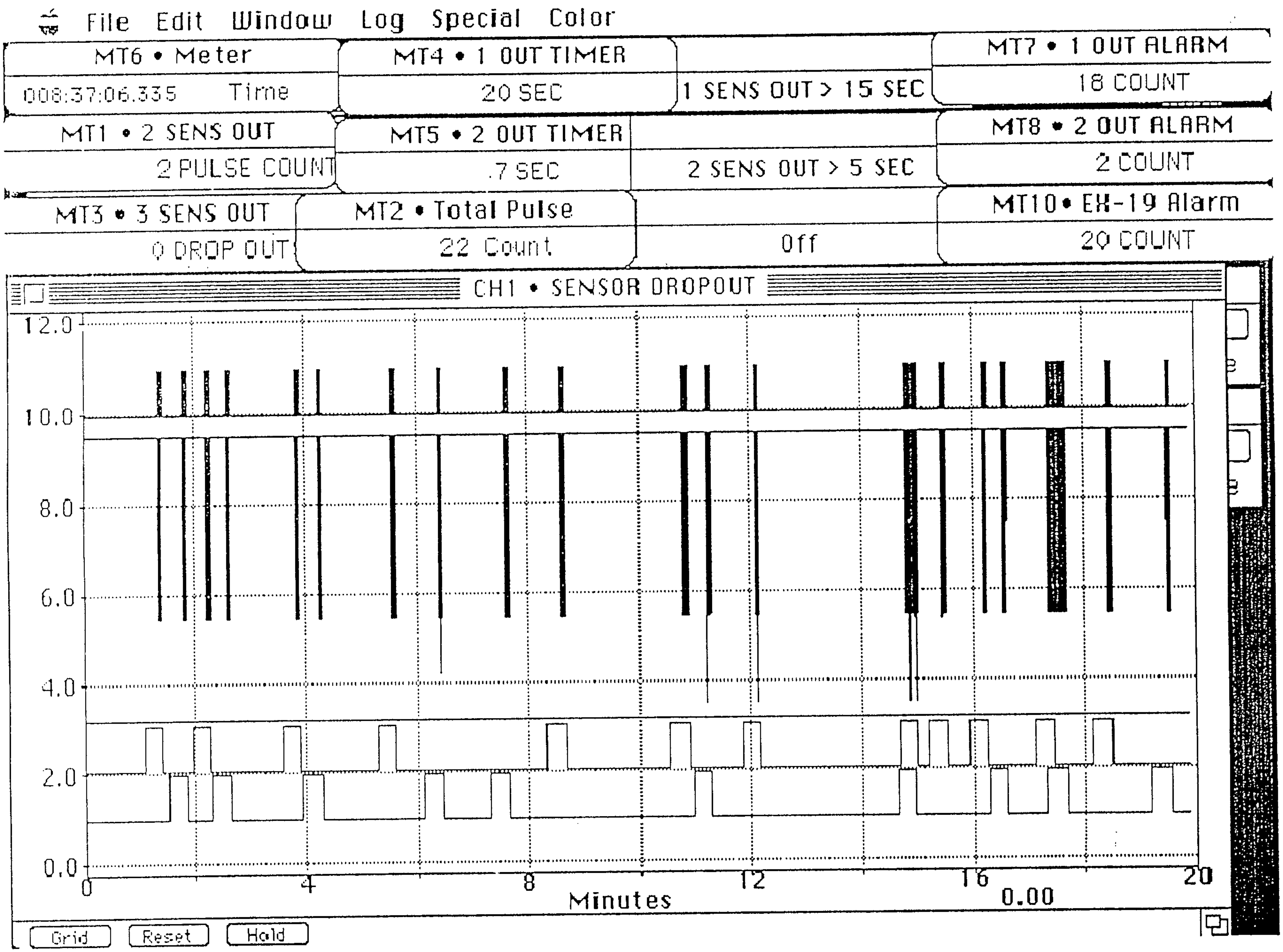


Figure A2. Macintosh/UBA Alarm Tracking Chart.